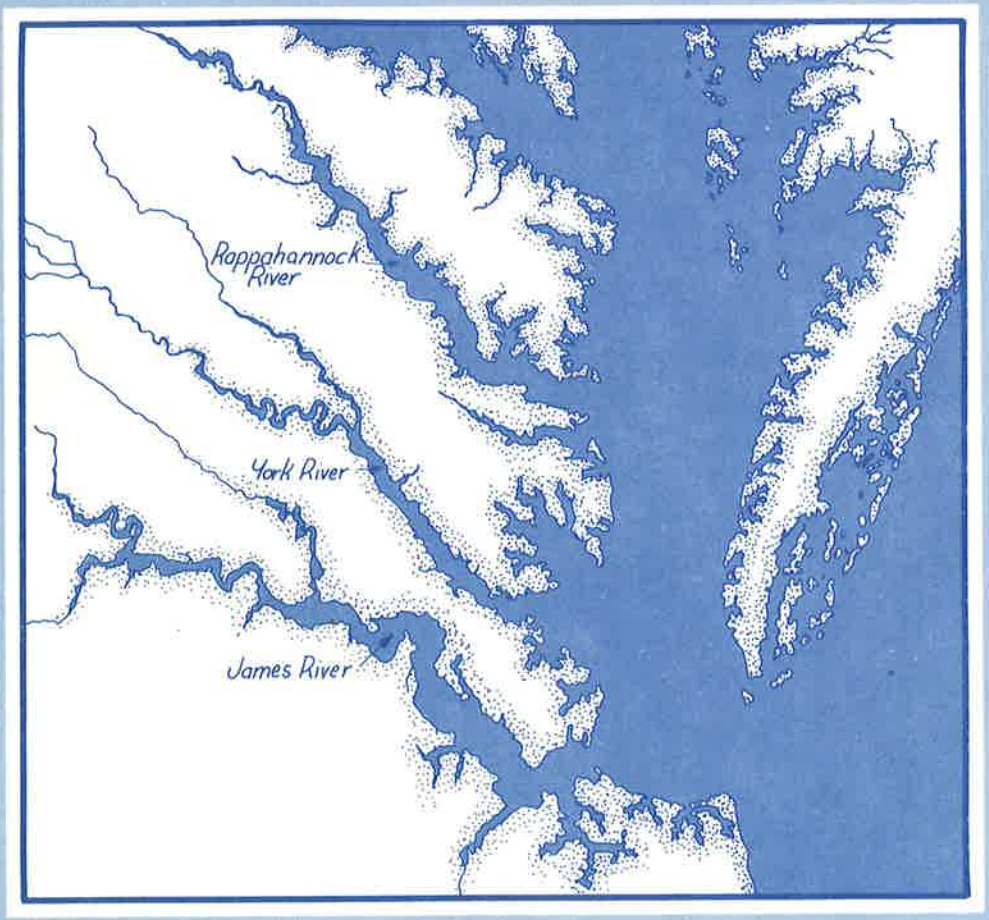
TRIBUTARY WATER QUALITY 1986

CHARACTERIZATION REPORT



Chesapeake Bay Water Quality Monitoring Program
Chesapeake Bay Office
Virginia Water Control Board

TRIBUTARY

WATER QUALITY

1986

CHARACTERIZATION REPORT

prepared by

CHESAPEAKE BAY OFFICE

VIRGINIA WATER CONTROL BOARD

2111 N. HAMILTON ST.

RICHMOND, VA. 23230

NOVEMBER 1987

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ACKNOWLEDGMENTS

The contents of this report, from the field sampling through final data analysis, represents the work and dedication of a large number of persons who should be recognized for their efforts. The field sampling was conducted by the Tidewater and Piedmont Regional Office of the Virginia Water Control Board (VWCB). The Piedmont Regional Office also provided staffing for the chlorophyll analyses. The nutrient laboratory of the Division of Consolidated Laboratory Services provided the analytical services. The Division of Information Services of the VWCB was responsible for the entry of data. The Graphics Communication Office assisted in cover design and layout.

The Chesapeake Bay Office was responsible for data management, analysis and reporting. The storage and analysis of the data was performed on the Chesapeake Bay Program Computer. This monitoring program is an element of the Bay wide monitoring program coordinated through the Chesapeake Bay Program Monitoring Subcommittee. Any questions concerning this report or the Chesapeake Bay Monitoring Program in Virginia can be directed to Robert Siegfried or Frederick Hoffman (804-257-6683).

I. EXECUTIVE SUMMARY

1. During the summer of 1984, the Commonwealth of Virginia established the Tributary Water Quality Monitoring Program as part of the Chesapeake Bay Monitoring Program, which includes water quality and biological monitoring of the Bay and its tributaries. The tributary program includes 32 stations from the fall line to the mouths of the Rappahannock, York, and James rivers. A variety of physical and chemical measurements are collected twenty times per year.

2. The Tributary Water Quality Monitoring Program has three major objectives. First, to describe or characterize the current water quality conditions. Second, to detect long-term trends in water quality due to increased nutrient loadings or management actions to control nutrients. The third objective is to improve our understanding of the processes that control water quality and its relationship to living resources.

3. Streamflows were generally below normal during much of 1986. The late spring and early summer of 1986 was extremely dry. Although Hurricane Charlie increased streamflows in some basins in August, dry conditions continued through October 1986. Much of the southeastern United States experienced the worst drought conditions in 111 years. The low streamflows resulted in much higher than normal salinity during the summer and fall. The low flows also impacted nutrient concentrations and loadings.

4. The Rappahannock, and to a lesser extent the James, exhibited high nonpoint inputs of inorganic nitrogen from above the fall line during winter and spring. The York also exhibited a winter/spring pulse of inorganic nitrogen, but it originated below the fall line and may have been largely the result of natural wetlands processes.

5. The James exhibited dramatic increases in nitrogen in the Richmond and Hopewell areas due to the large loadings of nitrogen from point sources. The state's ammonia toxicity criteria was exceeded several times during the summer in the tidal freshwater James. Extensive instream nitrification was evident and contributed to the oxygen demand on the upper tidal James.

6. Phosphorus was higher at the fall line and upper tidal James than in the Rappahannock or the York. This was due to both very high fall line concentrations of orthophosphate and large loadings of orthophosphate from point sources in the upper tidal James. The phosphorus levels at the fall line of the James were higher than comparable rivers and have been increasing since the 1970's. This represents an important change in nutrient loadings to the tidal James river. The York river generally had higher phosphorus concentrations at the fall line than the Rappahannock.

8. The occurrence of nutrient limitation at the fall lines of the York and Rappahannock was equally divided between phosphorus and nitrogen. The James was predominately nitrogen limited at the fall line, due to extremely high orthophosphate concentrations. The tidal waters of the Rappahannock were generally phosphorus limited, due to low phosphorus concentrations.

The tidal York was also predominately phosphorus limited, except in the transition zone where elevated particulate phosphorus concentrations resulted in intermediate ratios. In the James, large inputs of both phosphorus and nitrogen created complex changes in the limiting nutrient. In general, the limiting nutrient shifted from nitrogen to phosphorus as the river flowed from the fall line toward the estuary. Understanding this complex shift in nutrient limitation in the James is important in management of nutrients in the river.

9. Chlorophyll-a concentrations exhibited two major seasonal peaks. In the estuary, chlorophyll-a peaked in the late winter and early spring, with concentrations averaging 16 to 35 ug/l. The second peak was located in the tidal freshwater areas of the James and Rappahannock. In the James, chlorophyll-a concentrations here averaged between 35 to 51 ug/l, with maximums of over 70 ug/l, from the spring through the fall. The Rappahannock exhibited an average here of 26 ug/l during the summer and fall. Of the three rivers, the tidal freshwater James exhibited the most intensive and prolonged peaks in the concentration of chlorophyll-a. The Rappahannock exhibited strong peaks in chlorophyll-a in both estuarine and tidal freshwater areas. The York did not appear to experience a peak in chlorophyll-a in tidal freshwater.

10. Contrary to intuition, the most anthropologically impacted river, the James, experienced the least hypoxia (low dissolved oxygen) in its lower tidal portion. The lower Rappahannock and the lower York experienced hypoxia during the summer despite lower nutrient loadings. Important hydrological differences between the James, York, and Rappahannock may be responsible for this difference. Due to these circulation differences, the York and Rappahannock rivers may be more susceptible to the impact of increased urbanization than the James.

11. The following recommendations for modifications to the present program are preliminary, but will be reviewed and implemented by January 1988:

    - Modify station locations to increase coverage in areas such as the upper Rappahannock where coverage is minimal, and reduce coverage where there are redundant stations.

    - Reduce the number of nutrient analyses with results below detection limit by increasing the sensitivity of the laboratory methods and streamlining the range of nutrient analyses performed.

    - Redefine the salinity based segmentation to more accurately reflect the current and historical data.

    - Begin collecting measurements of total suspended solids at all stations. This will yield valuable additional ecological information with little additional effort.

II. INTRODUCTION

As part of the Chesapeake Bay Program, the Commonwealth of Virginia is engaged in extensive water quality and biological monitoring of the Virginia portion of the Chesapeake Bay and its tributaries. All of the monitoring programs have three basic objectives:

- The description or characterization of the current conditions which will constitute a 'baseline'.

  The establishment of a 'baseline' requires several years of data in order to identify the natural variation due to seasonal and freshwater flow related changes that occur in a system.

- Once a 'baseline' is established, identification of long-term spatial and temporal trends.

  Accurately determining trends in a system as large and variable as the Chesapeake Bay and its tributaries requires a large amount of data collected over a broad area for a long period of time.

- Improvement of our understanding of the processes that control the water quality of the Bay and the relationship between water quality and the living resources.

  While many of these relationships may require specific experimental research, a large amount of information can be gained through the integration of the water quality and biological monitoring programs and detailed analysis of the data collected within these programs. This integrated approach is especially important since this is the first time that water quality and biological data for the entire Bay and its tributaries have been collected and examined at the same time.

Achieving these objectives will give us a basis upon which to make judgements about the present condition of the Chesapeake Bay and its tributaries, to measure the effectiveness of pollution control strategies, to provide verification and calibration for water quality modeling efforts, and to allow for better informed management decisions.

In the summer of 1984, the Environmental Protection Agency, the Commonwealth of Virginia, and the State of Maryland instituted the mainstem water quality monitoring programs to study the Chesapeake Bay. The Commonwealth of Virginia also developed and instituted the tributary water quality monitoring program. This program will complement the efforts within the mainstem of the Bay and provide vital information about the James, York, and Rappahannock rivers as well as some of their major sub-tributaries. During the 1984-1986 biennium, Virginia also initiated plankton and benthic monitoring programs in the mainstem and tributaries. The benthic program samples eleven tributary and five mainstem stations four times per year. The plankton program samples six tributary and seven mainstem stations up to twenty times per year. All of the stations sampled under the biological programs are also monitored for water quality, thus allowing for the integration of water quality information with the biological data.

The objective of this report is to present the tributary water quality data collected from December 1985 through November 1986. This report will focus on the James, Rappahannock, York, and Pamunkey rivers. Individual stations located on the Appomattox, Chickahominy, Mattaponi, and Corrotoman rivers will be reported on seperately. This report is a description of the conditions or a 'characterization' of the water quality during the reporting period using simple statistics and graphical presentations. Each chapter has a brief discussion of the concepts involved, followed by presentation of the monitoring results. Data presentations first focus on each individual river system, then a general comparison between the rivers is made. An appendix which presents tables of summary statistics for each station has been bound separately and is available upon request. In addition to water quality results, this volume describes the current program, discusses some of its limitations, and plans for future program changes.

The second major objective of this monitoring program is trend detection. A volume covering the 1984-1986 data is planned for publication in spring of 1988 and will use advanced statistical procedures to better define the spatial and temporal trends in the data. The results of the various Chesapeake Bay Monitoring Programs are reported in the following publications. Copies of these reports can be obtained through the Chesapeake Bay Office of the VWCB. The report title, period of data covered, authors, and data published are cited.

PUBLICATIONS ON THE CHESAPEAKE BAY MONITORING PROGRAMS

- The State of the Chesapeake Bay 1984 - 1985; CBP Monitoring Subcommittee (1987).
- The State of the Chesapeake Bay 1984 - 1985 Compendium; CBP Monitoring Subcommittee (1987).
- Tributary Water Quality 1984 - 1985 Characterization Report; Chesapeake Bay Office, Virginia Water Control Board (1987).
- Organic Compounds in Sediments from Chesapeake Bay and its Tributaries 1984 - 1986; Paul deFur, VIMS (1986).
- Lower Chesapeake Bay Mainstem Plankton Monitoring Program July 1985 - June 1986; R.S.Birdsong, H.G.Marshall, R.W.Alden and R.M.Ewing, ODU (1987).
- Macrobenthic Communities of the Lower Chesapeake Bay March 1985 - June 1986; D.M.Daur, M.E.Ewing, and J.A.Ranasinghe, ODU (1987).
- Lower Chesapeake Bay Mainstem Water Quality Monitoring Program 1984 - 1985; R.W.Alden, A.J.Butt, and S.W.Sokolowski, ODU (1986).
- Lower Chesapeake Bay Mainstem Water Quality Monitoring Program 1985 - 1986; R.W.Alden, R.M.Ewing, A.J.Butt, and S.W.Sokolowski, ODU (1987).
- Summary of Chesapeake Bay Water Quality Monitoring Data 1984 - 1986; K.E.Curling, VIMS (1986).

III. PROGRAM DESCRIPTION

Under the tributary water quality monitoring program, data was collected at 28 tidal and 4 fall line stations located throughout the James, York, and Rappahannock river systems which are Virginia's major tributaries to the Chesapeake Bay. Between January and June of 1986 the U.S.G.S. conducted the field and laboratory work for the fall line stations. The Virginia Water Control Board (VWCB) Piedmont Regional Office has had responsibility for the collection of the fall line data since July, 1986. The 4 fall line stations were sampled once per month. All field work for the 28 tidal stations was conducted by the Tidewater and Piedmont Regional Offices of the VWCB and most laboratory analyses were conducted by the Virginia Division of Consolidated Laboratory Services. Chlorophyll samples were analyzed at the VWCB chlorophyll laboratory in the headquarters office.

The 28 tidal stations are sampled during monthly cruises between November and February. During the months of March through October, when biological activity is highest and water quality problems are most evident, cruises were scheduled twice per month. Sampling cruises are scheduled to coincide with low slackwater, the period during low tide when tidal currents are at a minimum. An effort was made to schedule tributary sampling close to the dates that Bay sampling was conducted. Due to tide and weather considerations, only about half of the tributary cruises fell within a week of the mainstem cruises. The actual sampling dates during the period covered by this report are listed in Table I.

The stations are located to characterize the salinity and circulation regimes found in the tributaries. In addition, several stations are located in smaller tributaries of the major rivers. Figures 3.1 through 3.3 depict the location of the stations within each river basin as well as major point sources of nutrients. Table II lists the station names, locations, river miles, and notes which stations are also included in the biological monitoring programs.

TABLE I

WATER QUALITY MONITORING SCHEDULE FOR 1986

MONTH	CRUISE	MAINSTEM	RAPP.	JAMES	YORK
DEC, 1985	31	9-10	3	4	5
JAN	32	6-8	14	15	16
FEB	33	10-12	11	12	13
MARCH	34	10-12	11	12	13
MARCH	35	24-26	25	26	27
APRIL	36	7-9	9	10	14
APRIL	37	21-23	24	28	29
MAY	38	12-14	7	11	12
MAY	39	26-28	22	27	28
JUNE	40	9-11	5	9	10
JUNE	41	23-25	23	24	25
JULY	42	14-16	7	8	9
JULY	43	28-30	21	22	23
AUG	44	11-13	5	6	7
AUG	45	25-27	19	20	21
SEPT	46	8-10	8	9	10
SEPT	47	22-24	22	23	24
OCT	48	6-8	6	7	8
OCT	49	27-29	20	21	22
NOV	50	17-19	24	25	

FIGURE 3.1

MAP OF RAPPAHANNOCK RIVER STATIONS

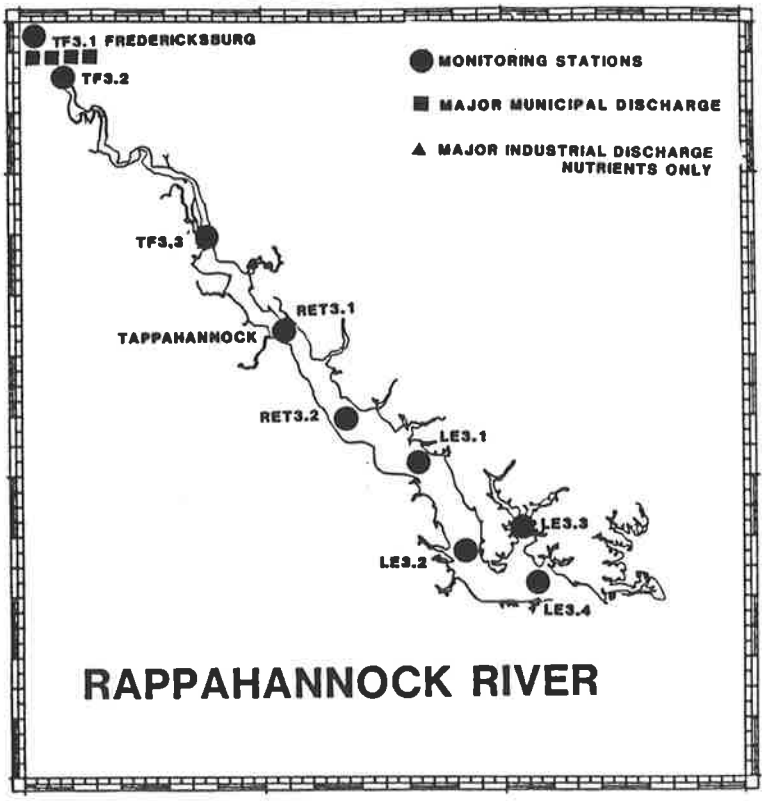


FIGURE 3.2

MAP OF YORK RIVER STATIONS

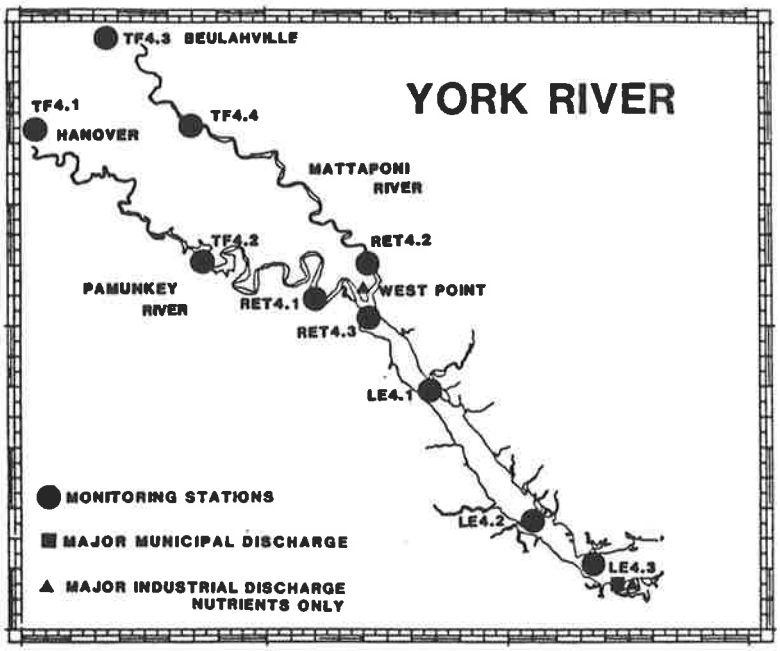


FIGURE 3.3

MAP OF JAMES RIVER STATIONS

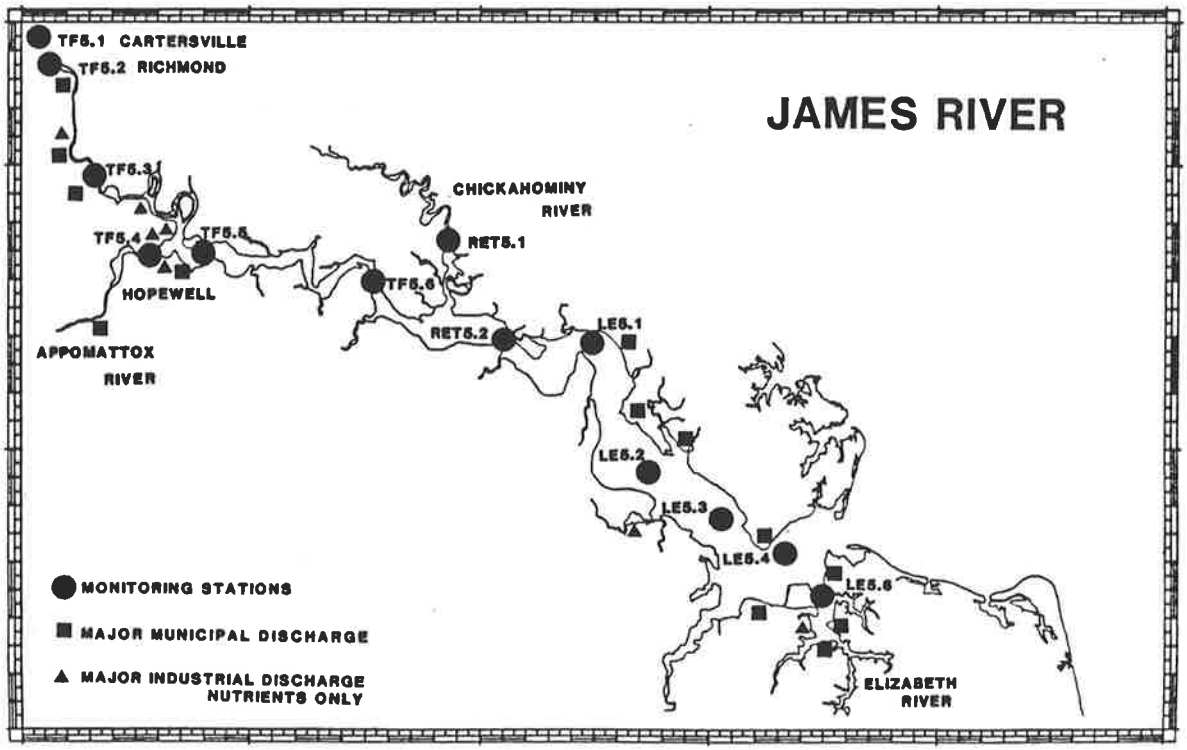


TABLE II

STATION, LOCATION, AND INFORMATION

Rappahannock River Basin

River	Sta. No.	STORET Code (River mile)	Location	Description
Rapp.	TF3.1	3-RPP110.57	Fredericksburg	Fall Line
Rapp.	TF3.2	3-RPP080.19	Port Royal	
Rapp.	TF3.3	3-RPP051.01	Buoy 40	Plankton, Benthos
Rapp.	RET3.1	3-RPP042.12	Buoy 10	Plankton, Benthos
Rapp.	RET3.2	3-RPP031.57	Buoy 16	
Rapp.	LE3.1	3-RPP023.52	Buoy 11	
Rapp.	LE3.2	3-RPP017.72	Near Buoy 8	Benthos
Corrotoman	LE3.3	3-CRR003.38	Buoy 6	
Rapp.	LE3.4	3-RPP010.60	Orchard Point	

York River Basin

River	Sta. No.	STORET Code (River mile)	Location	Description
Pamunkey	TF4.1	8-PMK082.34	Hanover	Fall Line
Pamunkey	TF4.2	8-PMK034.17	Whitehouse	Plankton, Benthos
Mattaponi	TF4.3	8-MPN054.17	Beulahville	Fall Line
Mattaponi	TF4.4	8-MPN029.08	Walkerton	
Pamunkey	RET4.1	8-PMK006.36	South of Lee Marsh	
Mattaponi	RET4.2	8-MPN004.39	Muddy Point	
York	RET4.3	8-YRK031.39	Buoy 57	Plankton, Benthos
York	LE4.1	8-YRK022.70	Buoy 44	Benthos
York	LE4.2	8-YRK011.14	Buoy 34	
York	LE4.3	8-YRK004.56	Buoy 26	Benthos

TABLE II (CONTINUED)

STATION, LOCATION, AND INFORMATION

James River Basin

River	Sta. No.	STORET Code (River mile)	Location	Description
James	TF5.1	2-JMS157.29	Cartersville	Fall Line
James	TF5.2	2-JMS110.30	Mayo's Bridge	Head of Tide
James	TF5.3	2-JMS099.30	Buoy 157	
Appomattox	TF5.4	2-APP001.53	Buoy 8	Mouth of river
James	TF5.5	2-JMS075.40	Buoy 107	Plankton, Benthos
James	TF5.6	2-JMS055.94	Buoy 74	
Chickahominy	RET5.1	2-CHK008.28	Shipyard Landing	
James	RET5.2	2-JMS042.98	Swann's Point	Plankton, Benthos
James	LE5.1	2-JMS032.59	Buoy 36	
James	LE5.2	2-JMS021.04	Buoy 12-13	Benthos
James	LE5.3	2-JMS013.10	Bouy 15	
James	LE5.4	2-JMS05.72	Buoy 9	Benthos
Elizabeth	LE5.6	2-ELI02.00	Buoy 18	

The types of data collected fall into two basic groups. At each station a vertical profile of temperature, dissolved oxygen, salinity, and conductivity is collected. These measurements are taken one meter below the surface and then every two meters downward through the water column until a depth of one meter above the sediment. A dissolved oxygen sample for Winkler titration and pH readings are also collected from the surface and bottom depths. A Secchi reading is taken to measure turbidity. Sampling is conducted directly from bridges at several stations located in the tidal freshwater region of the three rivers. This simplifies sampling but sometimes results in profiles and secchi readings being unavailable due to the height of the bridge above the water.

In addition to the physical parameters measured, samples are collected for nutrient analysis at one meter below the water surface and one meter above the bottom. The types of nutrient analyses conducted by the Virginia Division of Consolidated Laboratory Services are listed in Table III, along with detection limits and the EPA reference number for the analytical method. The analytical procedure for Ammonium/Ammonia determines the sum of Ammonium plus un-ionized Ammonia. The relative contribution of each form is a function of PH and temperature. Under normal conditions the major form is Ammonium, therefore this report uses the term 'Ammonium'. Chlorophyll samples were analyzed by VWCB staff.

TABLE III

LISTING OF NUTRIENT ANALYSES

NUTRIENT	DETECTION LIMIT (MG/L)	EPA METHOD(1)
Total Kjeldahl Nitrogen (TKN)	0.1	351.2
Nitrate (NO3 as N)	0.05	353.1
Nitrite (NO2 as N)	0.01	353.2
Ammonium/Ammonia (NH34 as N)	0.05	350.1
Total Phosphorus (TP as P)	0.01	363.4
Total Dissolved Phosphorus (TDP as P)	0.01	365.1
Orthophosphate (PO4 as P)	0.01	365.3
Total Organic Carbon (TOC as C)	1.0	415.1
Silica (Si as SiO4)	0.1	370.1

(1) Methods for Chemical Analysis of Water and Wastes, EPA, 1979.

IV. PHYSICAL VARIABLES

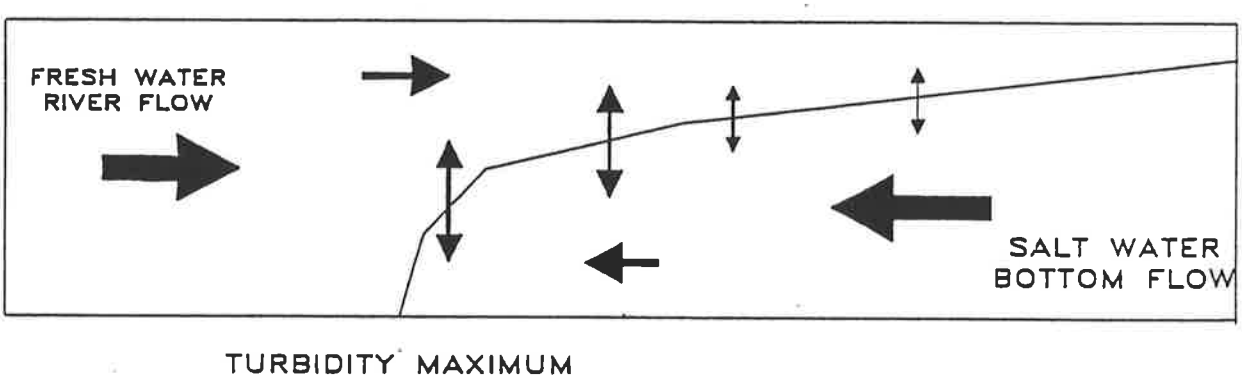
CIRCULATION

A rise in sea level after the last ice age flooded large river valleys and created the Chesapeake Bay and its major tributaries. As the tributaries flow toward the Chesapeake Bay they undergo several hydrological changes. The geological feature called the fall line separates the free flowing river from the tidally influenced river. As the tidal freshwater flows toward the mouth of each river it encounters saline water intruding upriver from the Chesapeake Bay, creating an estuarine environment. In general, the tributaries can be described as partially mixed estuaries with a lighter, lower salinity surface layer flowing down river over a denser, more saline bottom layer which is flowing up the estuary from the Bay (Figure 4.1).

These two layers of water have two important areas where mixing and diffusion of materials takes place. These mixing areas result in density gradients due to differences in salinity, and to a lesser extent, temperature. The major gradient is in the longitudinal direction or along the length of the river, where freshwater mixes with the incoming saltwater. This longitudinal density gradient is the force that drives the two-layered estuarine circulation. The strength of the longitudinal gradient is dependant on the length of the mixing zone between fresh and saline waters and the magnitude of the increase in salinity along the river's length. A strong longitudinal gradient (i.e. large salinity change over a short distance) results in a strong net nontidal flow up the estuary in the bottom layer, which can dramatically influence nutrient and dissolved oxygen dynamics.

FIGURE 4.1

DIAGRAM OF ESTUARINE FLOW



The area of mixing around the upriver limit of saltwater intrusion is often called the 'salinity transition' zone. This area of the river experiences the most dramatic changes in salinity in response to tides, changing streamflow, and climatic events. In this area of increasing salinity much of the material suspended in the freshwater layer flocculates and settles into the bottom layer and is then transported back upriver where it is reintroduced into the surface layer or settles to the sediment. This cycle creates an area of high turbidity, resuspension and deposition rates; thus the alternative name is 'turbidity maximum' zone. The estuary tends to retain material instead of exporting it down river, making the estuary a trap for nutrients, sediment, and toxics instead of being capable of flushing itself clean. This characteristic is important in our understanding of the relationship between the Chesapeake Bay and its tidal tributaries.

Another important gradient in the estuarine system is in the vertical direction. The vertical density gradient is often termed stratification. The interface between the surface and bottom layers is called the pycnocline. It is defined as the area in the water column with the greatest vertical rate of change in density, usually the depth which exhibits the greatest vertical change in salinity. Stratification is typically strongest midway between the upriver extent of salinity intrusion and the river mouth. It is also stronger during low slack water and neap tides when tidal mixing forces are reduced and during periods of high freshwater flows or warming of surface waters. Winds and storms, strong tides, and cooling temperatures can result in a decrease or break up of vertical density stratification. In strongly stratified systems vertical mixing is inhibited and exchanges of nutrients and dissolved oxygen between the surface and bottom waters are reduced.

The two major forces responsible for the salinity structure of the tributaries are freshwater streamflow and sea level fluctuations. Freshwater input is highly variable between the different river basins and is episodic in nature, but is relatively easy to measure with gauging stations. The seasonal pattern of high freshwater flows in the late winter/early spring and low flows in the late summer/early fall are reflected in the seasonal changes in salinity. Sea level exhibits a low in January and a high in September, but hurricanes and 'Northeaster' storms can create short term local rises in sea level. Superimposed over the fluctuations in streamflow and sea level are the tidal cycles. The Bay and its tributaries experience twice daily tidal fluctuations which are modified by a fortnightly cycle of stronger and weaker tidal forcing (spring/neap cycle). In order to reduce the confounding influences of tidal cycles, most cruises are conducted near low slackwater.

The Tributary Water Quality Monitoring Program collects both temperature and salinity data, which are important in defining density gradients and seasonal patterns that control many biological activities. In addition to the physical data collected under this program, other sources of data are helpful in interpreting the monitoring results. Long-term freshwater discharge data for the fall line stations are collected by the U.S.G.S. This data is valuable in interpreting not only streamflow data and its effect on salinity but also the contribution of nutrients from above the fall line. Within the discussion of streamflow

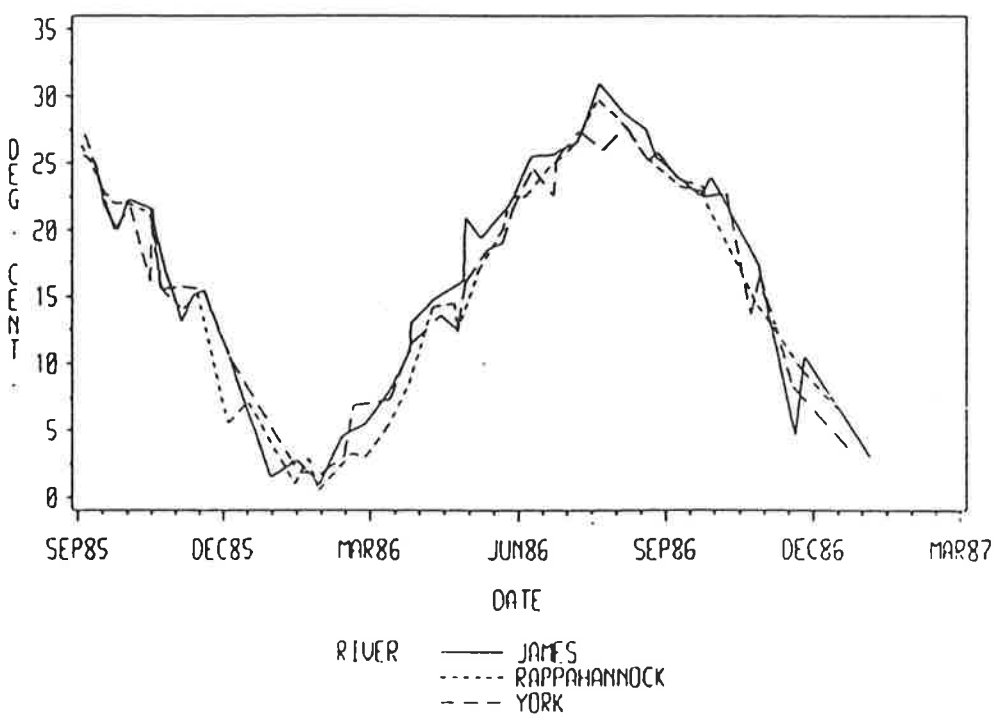
for each river, the long-term median monthly flows are compared with the mean monthly flow for the months of October 1985 through December 1987. The long-term median streamflow was used instead of the long-term mean since medians are less influenced by rare events, such as major hurricanes. A source of freshwater inflow not measured by the fall line gauges is the runoff from the drainage basins below the fall line. Deviations from normal rain fall and air temperature are reported monthly by the National Climatic Data Center. The Tidewater and Eastern Piedmont Divisions generally includes the area below the fall line.

WATER TEMPERATURE

Figure 4.2 depicts seasonal fluctuations in water temperature in each river. Differences in sampling dates and number of stations are responsible for some of the differences between the rivers, and are overshadowed by the seasonal changes in temperature. The tidal freshwater experiences wider variations in temperature than the estuary, which is influenced by the more stable oceanic waters. The water temperature cycle typically has a minimum in January and a maximum in late July or August. Air temperatures were below normal for much of the winter of 1986. July, August and October experienced above normal air temperatures.

FIGURE 4.2

WATER TEMPERATURE



Annual seasons were defined to allow comparisons within years and between years. The traditional three month seasonal divisions do not reflect the actual temperature changes in the rivers due to the time lag between air temperature and water temperature. The water tends to warm more slowly in the spring and cool more slowly in the fall than does the atmosphere. There are also other factors such as streamflow and hypoxia that are characteristic of certain seasons, but are not accounted for by traditional seasons. The seasonal definitions used in this report are based primarily on water temperature, but also consider other factors. The average temperature for each individual cruise was calculated and then each set of river cruises was classified as a particular season. Table IV describes which months were included in each season. The same definitions for the seasons based on temperature were developed in the 1984-1985 report, but when applied to 1986 data results in the seasons encompassing slightly different months than in the previous report. Winter cruises are those with high streamflow and average temperatures below 10°C, which includes December through early March. Spring is the period of rapid warming from 10°C to 24°C, which occurred from March through May. Summer included those cruises which had average water temperatures above 24°C, which encompassed June through August. Fall was defined as the period of rapid decrease in temperature from 24°C to 10°C, occurring from September to November. Data for December 1986 will be evaluated as part of the winter season in the 1987 report.

TABLE IV

Definition of Seasons

SEASON	NUMBER OF CRUISES	MONTHS INCLUDED
Winter	4	Dec. 1985 - Early March
Spring	5	Late March - May
Summer	6	June - August
Fall	5	Sept. - Nov.

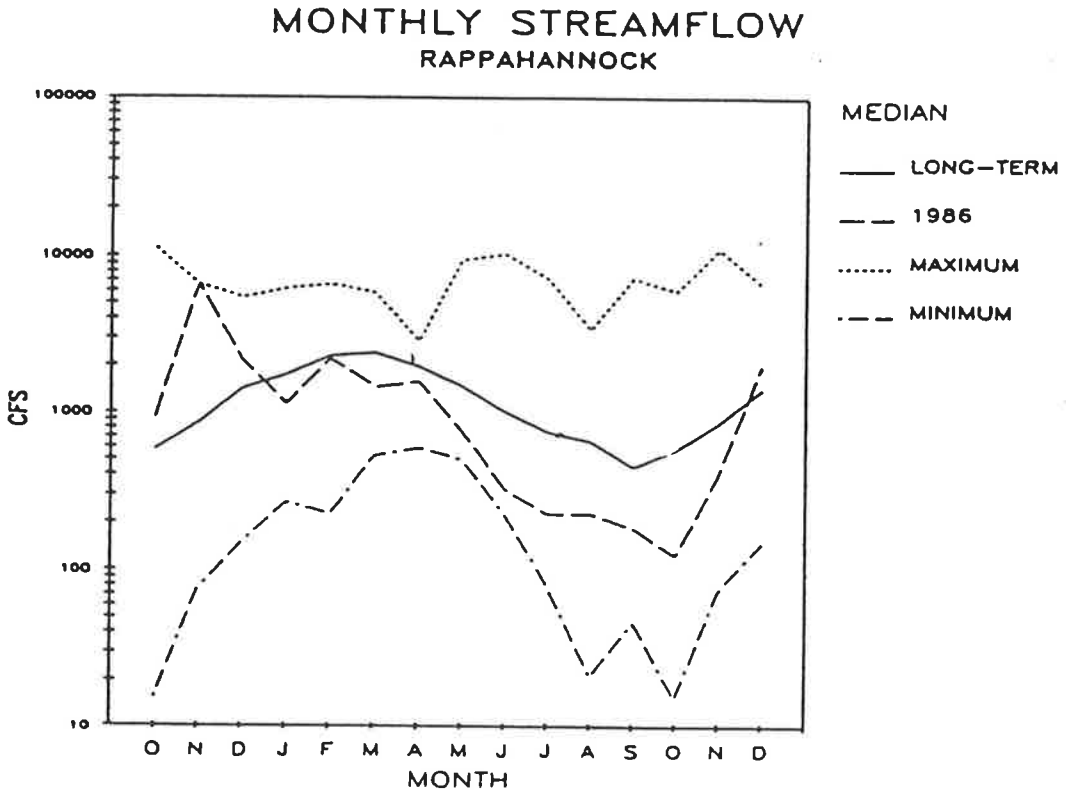
RAPPAHANNOCK RIVER

RIVER DISCHARGE

The fall line station on the Rappahannock is upstream of Fredericksburg, Virginia, and measures drainage from 1,596 square miles. This station was establish in 1910 and has a long-term median discharge of 1,631 cubic feet per second (cfs). The long-term median flow in the Rappahannock exhibits a seasonal peak in streamflow of approximately 2,000 cfs from February through April, then declines to below 750 cfs from July through October (Figure 4.3). Streamflows for most of 1985 were below normal, but storms in February, August, and Hurricane Juan in November, resulted in streamflows above normal during several months of the year. During 1986, streamflows were below normal during all months, especially between June and November. The average flow during October (122 cfs) was the fourth lowest on record

The extremely low flow conditions reflected the below normal rainfall during 1986. From December 1985 through October 1986, precipitation in the tidewater and eastern piedmont region was 40 to 70 percent below normal, except during August. Hurricane Charlie resulted in a 60 to 70 percent above normal rainfall during August in the tidewater and eastern piedmont regions. The impact of this storm was relatively minor and limited mainly to coastal areas and is not reflected in the streamflow at the fall line. While both 1985 and 1986 were considered to be dry years, winter and spring streamflows were higher in 1986, while streamflow during summer and fall of 1986 were less than in 1985.

FIGURE 4.3

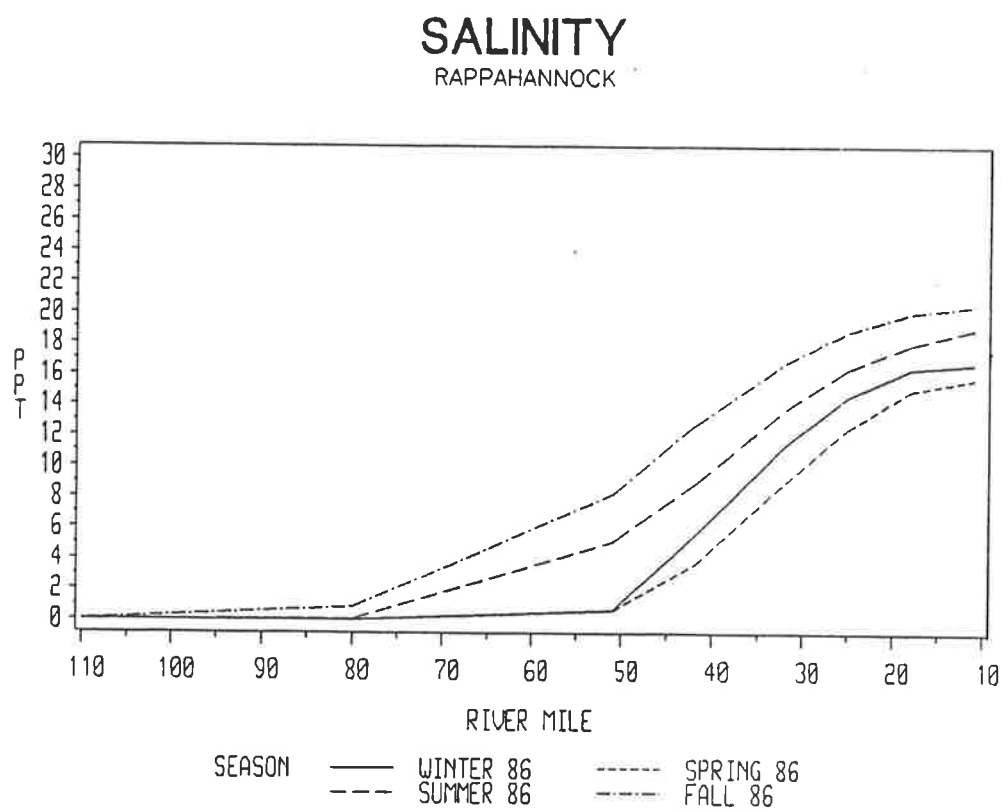


SALINITY

Figure 4.4 depicts the seasonal changes in the upriver extent of salinity intrusion. Salinity intrusion, defined as the upriver limit of salinity (0.5 ppt) in the bottom water, corresponds with the seasonal fluctuations in streamflow. The seasonal concentration of salinity for each station was calculated as the arithmetic average of all salinity profile data collected at that station during a specific season. Data for the upper tidal Rappahannock (miles 50 - 80) is limited; thus the true extent of salinity intrusion is not well defined. During winter, the upriver intrusion of salinity was limited to mile 50. During the spring, salinities were lower than in the winter, and there was evidence of highly stratified conditions near the river mouth. The summer and fall each exhibited a major increase in salinity of approximately 4 ppt over the previous season. Salinity intrusion reached a maximum (mile 80) in September 1986.

The decrease in salinity in the spring of 1986 is notable because it resulted from low salinities in the central Chesapeake Bay rather than increased streamflow in the Rappahannock. Streamflows in the Rappahannock were below normal during this period with only one major storm event during April. Surface salinity in the central Bay averaged 16 - 17 ppt in February and early March, but declined to 13 - 14 ppt by late March and April. The Susquehanna river experienced streamflows above normal during February and March, which may have been a major factor contributing to the lower salinities in the central Bay during March and April. Vertical stratification in the Bay also increased during this period.

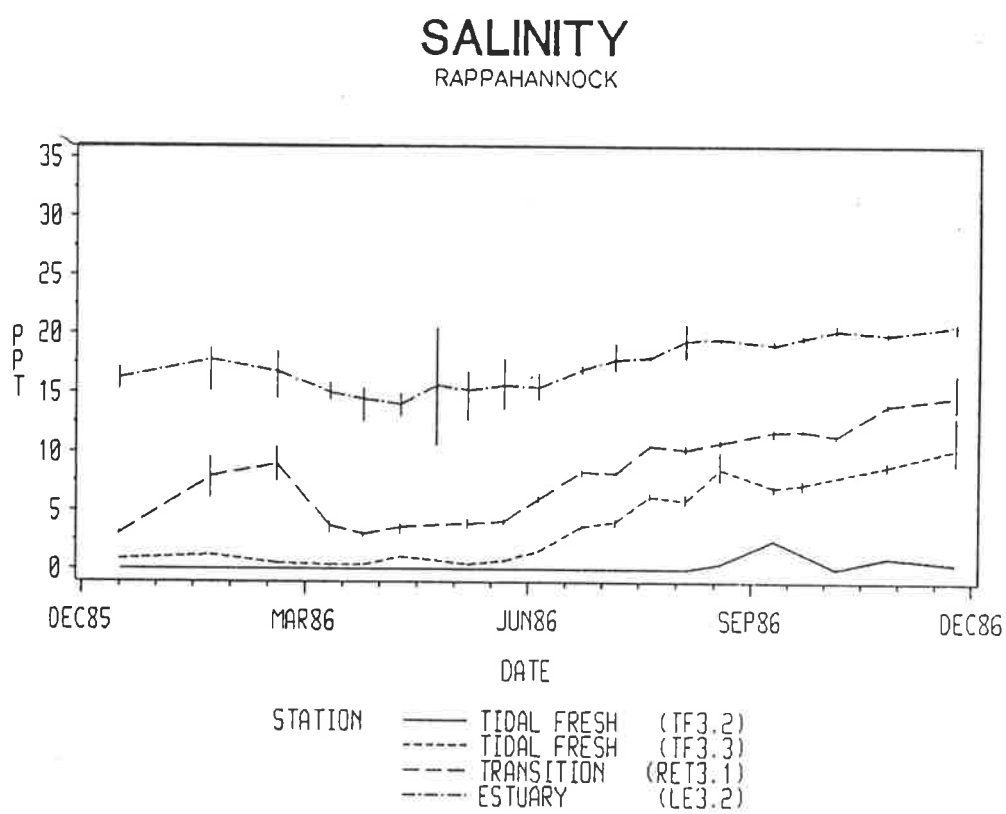
FIGURE 4.4



During the winter, the water column was generally well mixed, but by April the surface to bottom difference in salinity at some Bay stations was as great as 10 ppt. The vertical stratification seen in the Bay also appeared to be evident at the mouth of the Rappahannock, as indicated in Figure 4.5, where vertical bars depict the highest and lowest salinity recorded at selected stations. Station LE3.2 typically exhibits low stratification, but during the spring of 1986 the water column appears far more stratified than usual. A storm event in mid-April further intensified stratification during the late April cruise.

Temporal changes in salinity are also depicted in Figure 4.5. Station TF3.2 is generally tidal freshwater but during the fall of 1986 salinities of up to 1.2 ppt were recorded at this station. Station TF3.3 is typically freshwater during the high flows of winter and spring and oligohaline (0.5 to 5 ppt) during the summer and fall. Due to the higher salinities of 1986, this station was oligohaline throughout the winter and spring, and progressed into mesohaline conditions (5 to 18 ppt) during late summer and fall. The 'transition zone' station, RET3.1, averaged 4 to 13 ppt, thus making it mesohaline. As a result of the low streamflow conditions, the 'transition' zone stations were down river of the actual turbidity maximum. Estuarine stations ranged from 12 - 15 ppt in the spring to 19 - 20 ppt in the fall. These stations are predominately mesohaline during the winter through the summer, but as streamflow decreased, polyhaline conditions (18 plus ppt) prevailed during the fall 1986. While salinities in the spring and summer of 1986 were similar to those in 1985, the fall exhibited much higher salinity than in 1985.

FIGURE 4.5



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YORK RIVER

RIVER DISCHARGE

In the York River Basin, streamflow is measured at Hanover on the Pamunkey and at Beuhlaville on the Mattaponi. The Pamunkey gauge measures drainage from 1,081 square miles and the Mattaponi River gauge measures drainage from 601 squares miles. These long-term gauging stations were established in 1942. The long-term median streamflow for the Pamunkey and Mattaponi are 990 cfs and 553 cfs, respectively. Figure 4.6 indicates that the baseflows are very similar between the Pamunkey and the Mattaponi, but they respond differently to storm events. While an increase in discharge in both rivers is seen during a storm event, the Pamunkey responds quicker and with much higher flows than the Mattaponi. As a result, storm crests on the Pamunkey are narrower, more intense and peak sooner than those of the Mattaponi. The upper Mattaponi basin is composed of more wetlands and smaller drainages than the upper Pamunkey basin. These factors may act to dampen the Mattaponi's response to storms.

Streamflow peaks in February and March at over 800 cfs in the Mattaponi and over 1,500 cfs in the Pamunkey (Figure 4.7A&B). The seasonal period of low streamflow is usually July through October with flows below 400 cfs in the Pamunkey and below 300 cfs in the Mattaponi. As in the Rappahannock, the Pamunkey and Mattaponi experienced high streamflows in November and December 1985 due to Hurricane Juan. Flows for most of 1986 were below normal, except for May on the Mattaponi and

FIGURE 4.6

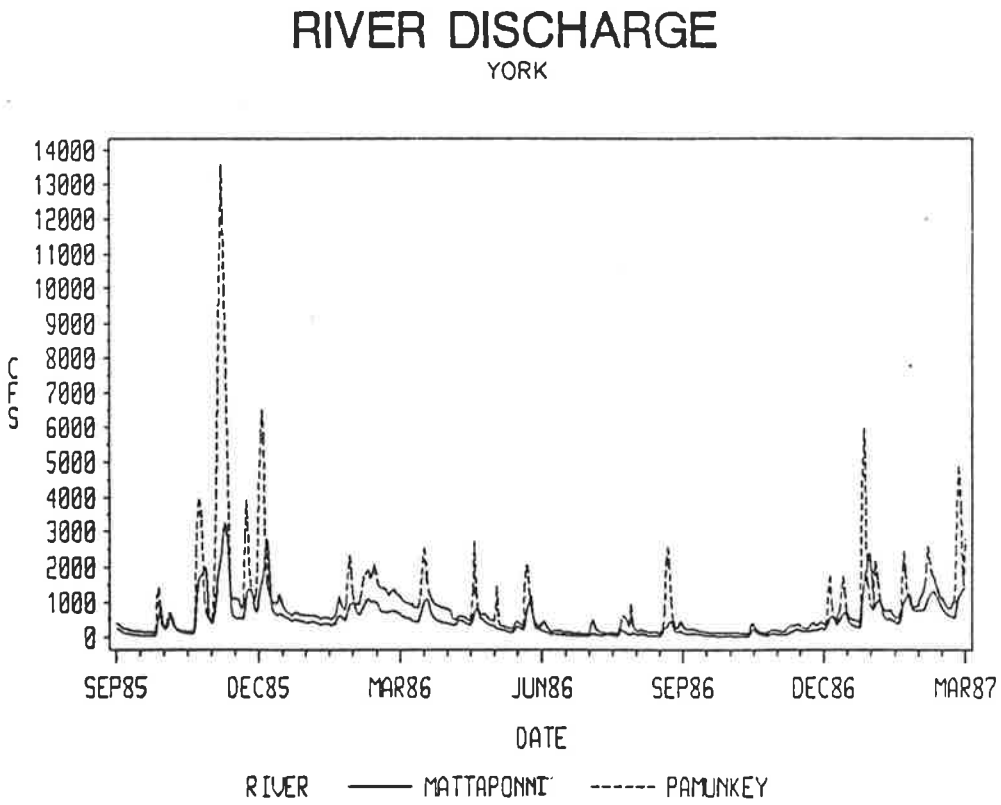


FIGURE 4.7A

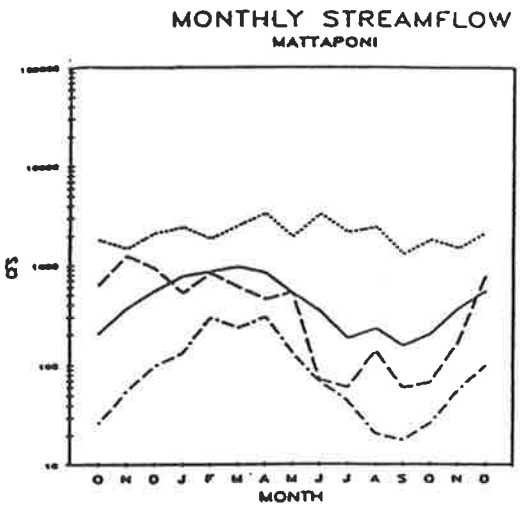
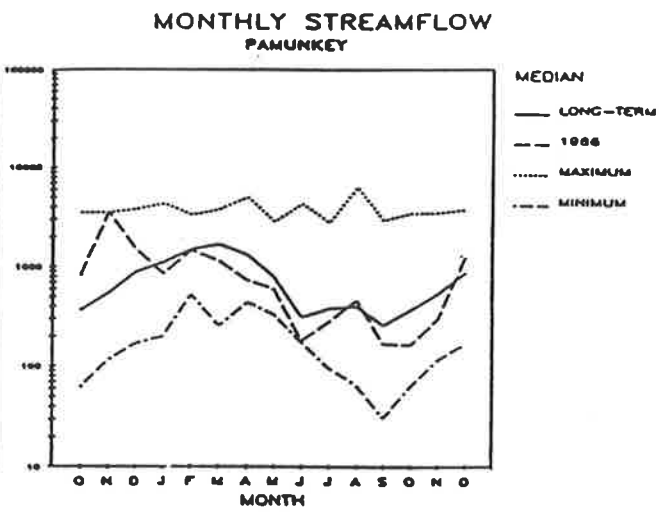


FIGURE 4.7B



August on the Pamunkey. Streamflows of 176 and 70.4 cfs during June were near record lows for the Pamunkey and Mattaponi, respectively. While both rivers showed increased flows in August due to Hurricane Charlie, streamflow in the Mattaponi still remained below normal for the month. Streamflows declined and remained low through the fall. Streamflows for most of 1985 were approximately 15 to 25 percent below normal but for the same period in 1986, flows were more than 30 percent below normal. Unlike 1985, when there was storm activity in February, August and November, 1986 experienced very little storm activity, except for August.

SALINITY

Salinity increased steadily from the winter through the fall as streamflow decreased, resulting in a four ppt increase in the average salinity between winter and late fall (Figure 4.8). Mile 45 was the upriver limit of salinity intrusion during the winter, but the intrusion progressed upriver to near mile 70 by the fall. The increase in streamflow in August due to Hurricane Charlie only temporally decreased salinities. Salinity in the transition zone rose steadily through the year, but the salinity near the mouth of the river averaged 20 ppt during the winter and spring, then increased to 25 ppt during the summer and fall. Salinities were generally lower in the winter of 1986 than during winter of 1985. The lower salinities in the central Bay during the spring did not greatly influence the York as it did the Rappahannock, although it may have been the cause of the slower rise in salinity at the mouth of the York.

FIGURE 4.8

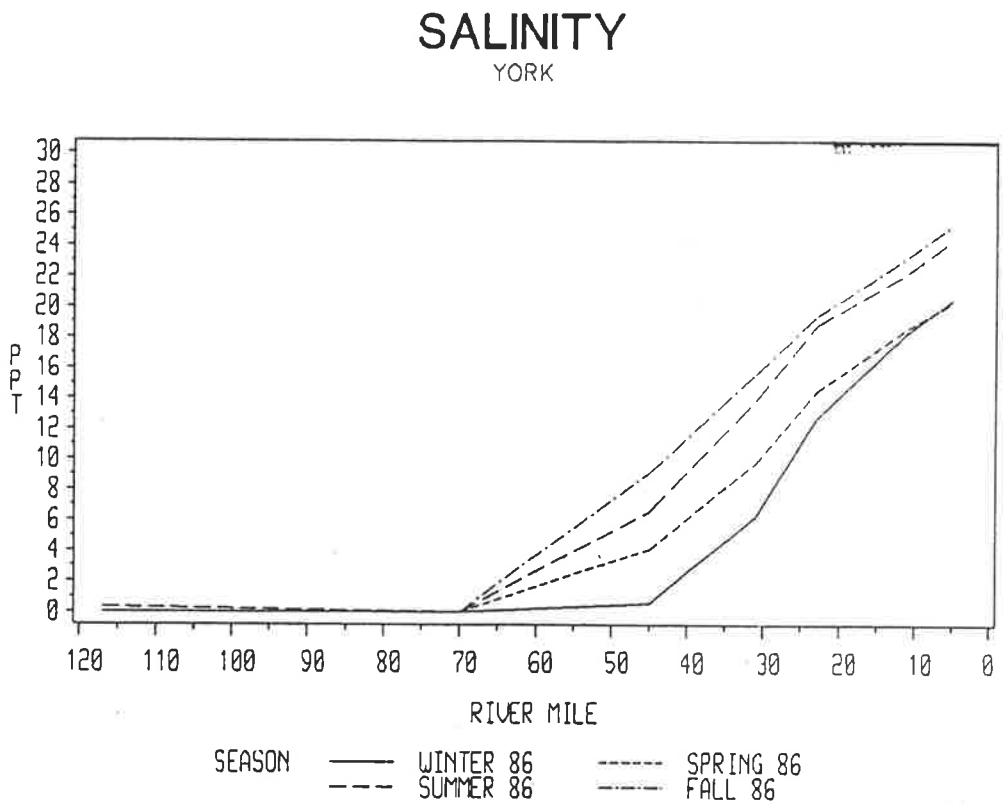
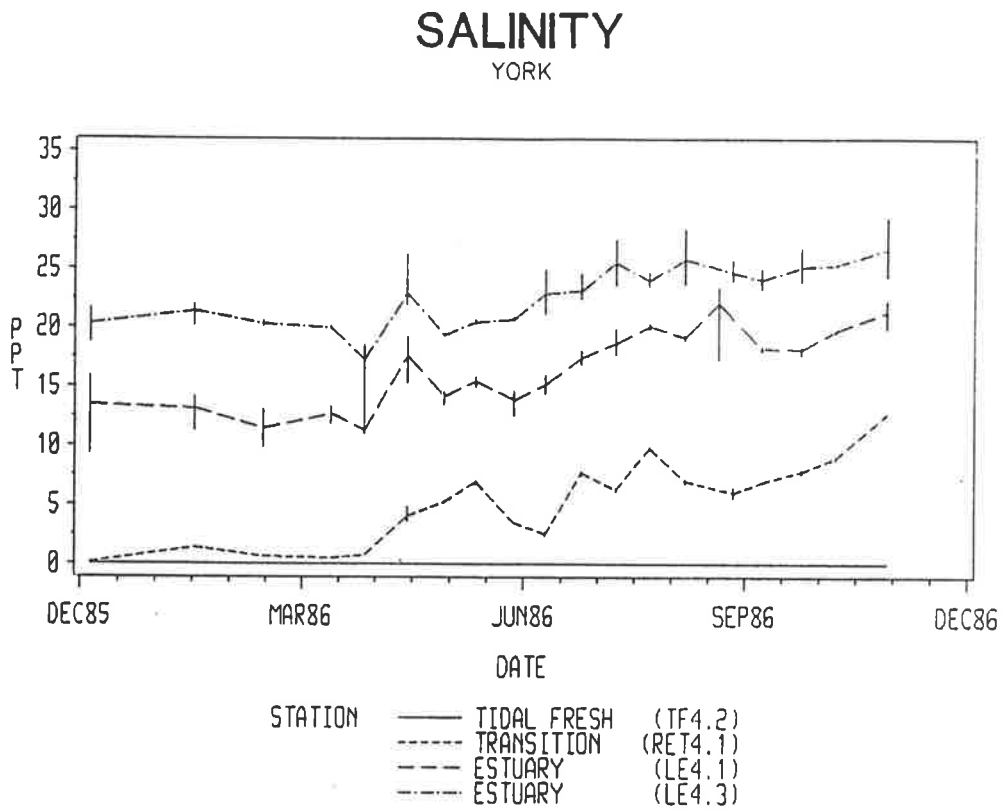


Figure 4.9 presents detailed salinity data for several selected stations in the York and Pamunkey rivers. Station TF4.2 on the Pamunkey is strictly tidal freshwater. One of the transitional stations is located several miles upriver of West Point on the Pamunkey, and the other is located in the York river proper, downstream of West Point. Oligohaline and low mesohaline conditions predominate at the upriver transition station (RET4.1) while the downstream station (RET4.3) was entirely mesohaline. The remaining stations in the York are composed of both mesohaline and polyhaline stations. Station LE4.1 exhibited mesohaline salinities while stations LE4.2 and LE4.3 were polyhaline with seasonal averages between 22 and 25 ppt. As seen in the Rappahannock, most of the stations experienced salinities during the fall which were much higher than normal.

FIGURE 4.9

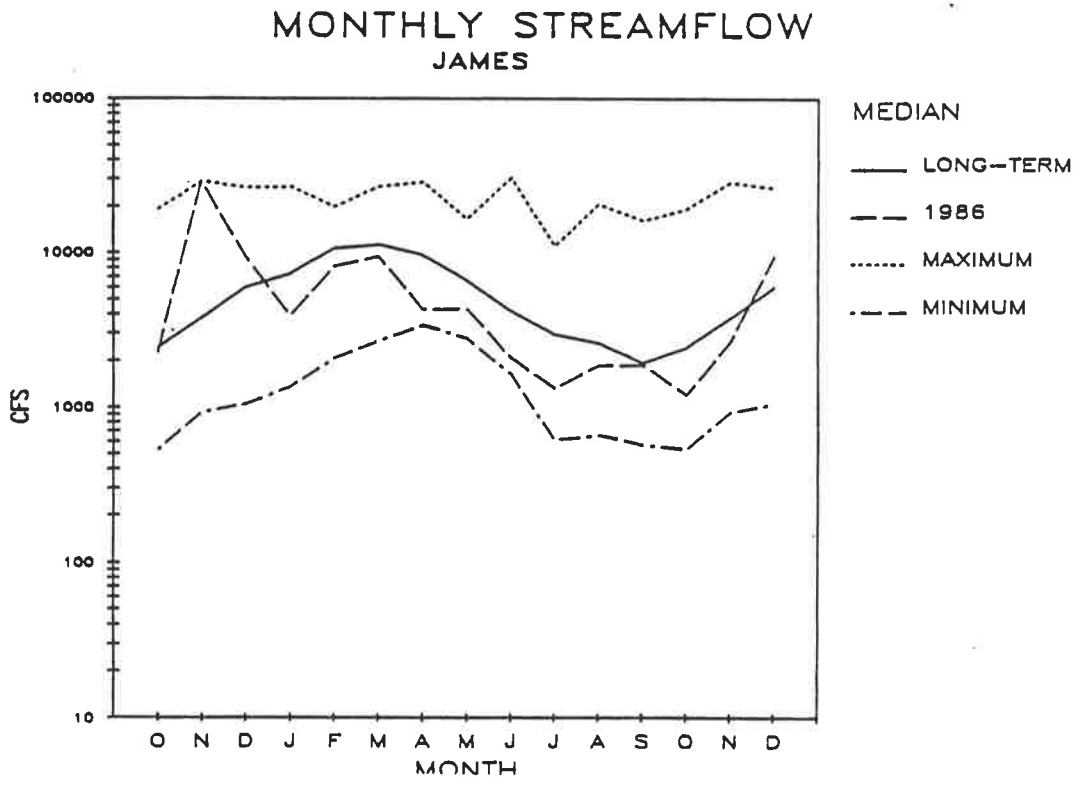

SALINITY
YORK
35
30
25
20
15
10
5
0
PPT
DEC85
MAR86
JUN86
SEP86
DEC86
DATE
STATION
TIDAL FRESH (TF4.2)
TRANSITION (RET4.1)
ESTUARY (LE4.1)
ESTUARY (LE4.3)

JAMES RIVER

RIVER DISCHARGE

The U.S.G.S established the fall line gauge at Cartersville, Virginia, in 1923. It is located at mile 157, approximately 50 miles upstream from the actual fall line in Richmond, Virginia (mile 110). The James river at Cartersville drains 6,257 square miles and has a long-term median flow of 6,433 cfs. The long-term median streamflow exhibits a seasonal peak of 10,000 to 12,000 cfs during late winter/early spring, and less than 4,000 cfs from July through November (Figure 4.10). November 1985 set a record flow for the month as a result of Hurricane Juan, which was the largest flood in the James Basin since Hurricane Agnes in 1972. During 1986 streamflow was below normal, especially from April through July. April recorded the fifth lowest streamflow for that month at 4,229 cfs. The above normal precipitation in August associated with Hurricane Charlie was apparent in the near normal August and September streamflows. In addition to the freshwater input from above the fall line of the James, the tidal estuary also receives freshwater from the Appomattox river. The Appomattox river long-term median discharge is 1,332 cfs. Flows during the spring of 1986 were not as low as 1985, but flows during the early summer were the lowest on record since 1970.

FIGURE 4.10



SALINITY

Changes in salinity generally reflect the patterns of freshwater streamflow. Based on analysis of slackwater data, salinity in the James typically increases by 4 ppt from early spring through late summer (Bradshaw and Kuo, 1987, Salinity Distribution in the James Estuary). Salinity intrusion varies from mile 33 during March and April to mile 53 during August - October. The long term average extent of salinity intrusion at low slack water is 44 ± 12 miles and 50 ± 11 miles during high slack water (Bradshaw and Kuo, 1987).

The seasonal extent of salinity intrusion is depicted in Figure 4.11. The upriver extent of salinity intrusion during the winter and spring was approximately 45 miles. During the summer and fall, intrusion ranged between mile 60 and 80. The James experienced a sharp increase in salinity between spring and summer which continued into the fall. Compared with the long-term average reported by Bradshaw and Kuo, the salinity intrusion in the James was 25 to 50 percent greater than normal during 1986.

FIGURE 4.11

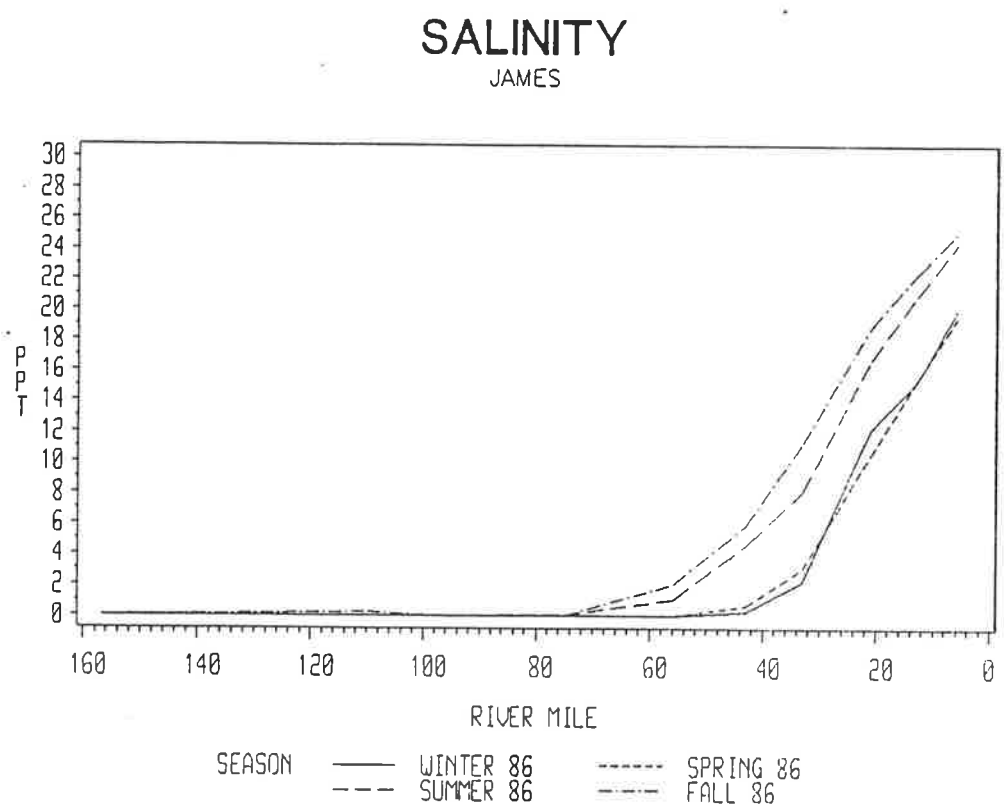
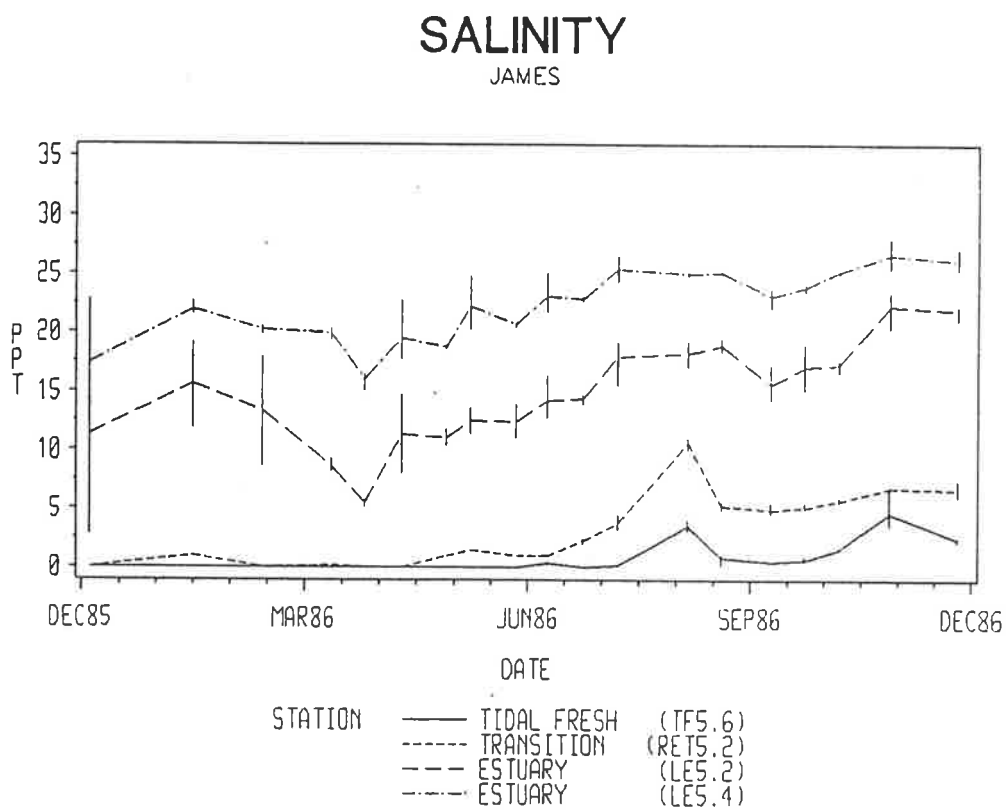


Figure 4.12 presents detailed information for several selected stations. All stations show a reduction of salinity in late March shortly after a major storm. Salinities also declined after Hurricane Charlie in August. Station TF5.6 is located at mile 56, which during typical low flow conditions is the station furthest upriver that salinity is detected. During 1986, TF5.6 exhibited salinities of up to 5 ppt in mid summer and late fall. The station located between Jamestown and the Chickahominy (RET5.2) generally exhibits freshwater and oligohaline conditions with salinities ranging from 0 to 5 ppt. By early August of 1986 salinity at this station was near 10 ppt. The estuarine stations have average salinities ranging from 10 - 16 ppt at LE5.2 to 20 - 26 ppt at LE5.4. Station LE5.2 shows a large vertical gradient in salinity, as depicted by the vertical bars in Figure 4.12, indicating a strongly stratified condition. The lower James has stations that remain either mesohaline and polyhaline through out the year.

FIGURE 4.12



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RIVER COMPARISONS

The seasonal and episodic patterns of streamflow contribute to determining the characteristics of each of Virginia's tidal tributaries and their impacts on the Chesapeake Bay. The York and Rappahannock rivers contribute only one fifth as much freshwater to the Bay as does the James. The James in turn contributes less than 20 percent of the total freshwater input to the Bay, the majority coming from the Susquehanna and Potomac rivers. While the fluctuations in streamflow in the Virginia tributaries may have a relatively minor impact on the Bay, these seasonal and annual changes have profound impacts within the tributaries themselves.

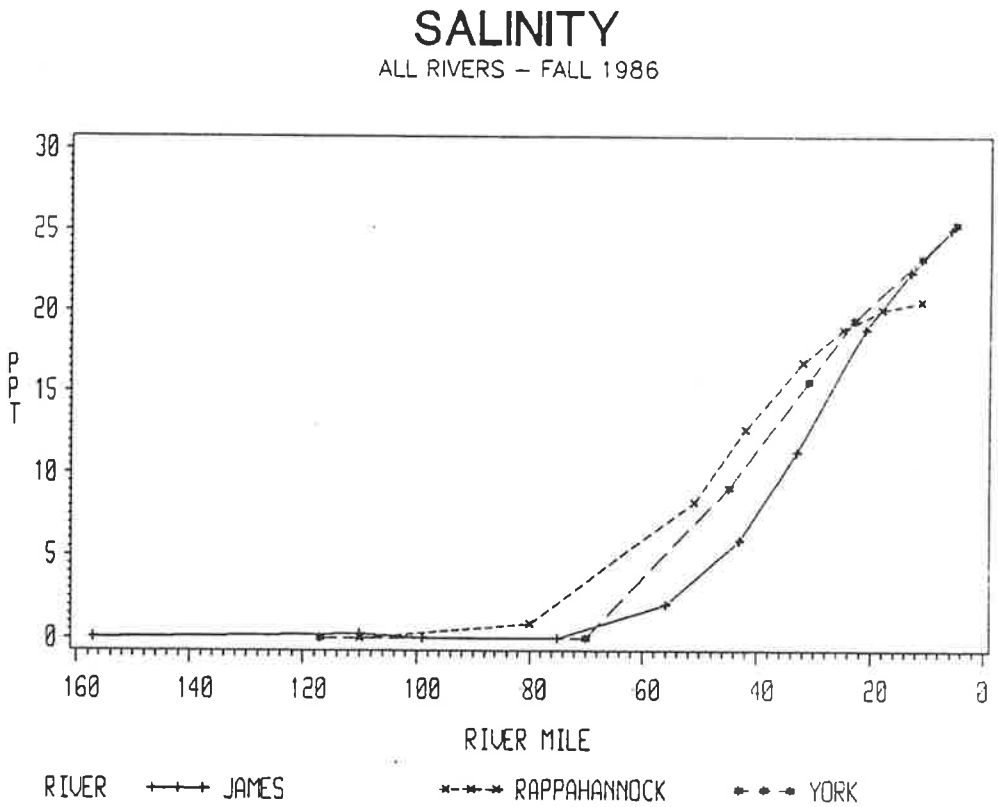
Streamflows were high in the early winter due in part to Hurricane Juan in November 1985, but by January flows were well below normal. Flows reached a peak in February and March, but were still below normal for these months. The spring and early summer were very dry. Streamflow in the York during June was one of the lowest recorded for that month. Coastal rains associated with Hurricane Charlie in August increased flow in the James and Pamunkey to near normal, but the Mattaponi and Rappahannock remained well below normal. Flows reached a minimum for the year in October.

SALINITY

In the winter, the Rappahannock upriver of mile 20 had salinity greater than the York or the James. During the spring, the salinity in the Rappahannock decreased, the York increased and the James remained the same. All rivers increased in salinity during the summer, but remained the same relative to each other. During the fall, all rivers showed continued increases in salinity, with the Rappahannock becoming more saline than the York. The relationship between streamflow and salinity is complex, but analysis of slackwater data from the James river has determined that 80-85 percent of the variation in the upriver extent of salinity intrusion can be explained by streamflow (Bradshaw and Kuo, 1987). Future analyses may produce similar results from the York and Rappahannock rivers.

A graphical comparison of the longitudinal distribution of salinity in the three rivers highlights several consistent features (Figure 4.13). The salinities at the mouth of the York and James are similar, but are usually 4 ppt higher than the mouth of the Rappahannock, reflecting the influence of lower salinity central Bay waters on the Rappahannock. The James consistently exhibits the sharpest decline in salinity in an upriver direction. The Rappahannock, despite the lower salinities at its mouth, has a more gradual upriver decline in salinity resulting in higher salinities upriver of mile 20 than the York or James. The York exhibits a mixture of characteristics seen in the Rappahannock and James. The mouth of the York has salinities similar to the James while upriver it exhibits a gradual decline in salinity similar to the Rappahannock. These differences between the rivers are the result of differences in the input of freshwater streamflow in each river and the salinity of the Chesapeake Bay near each river's mouth. Since the James is influenced by Bay water of higher salinity and has higher streamflows than the other rivers, it has the strongest vertical and longitudinal salinity gradient. The York becomes stratified during neap tides, but becomes well mixed after spring tides.

FIGURE 4.13



The Rappahannock has comparatively weak longitudinal and vertical salinity gradients, but can experience strong vertical gradients during high streamflow periods. Stratification breaks down somewhat during the spring/neap cycle and storm events, but not to the extent seen in the York river.

As discussed in the 1984-1985 report, the tributary stations exhibit a wide range of salinities and the current spatial segmentation of the stations into tidal freshwater (TF), riverine-estuary transition (RET) and lower estuary (LE) zones, is not adequate to describe the salinity characteristics of the tributaries. While the 1986 data provides an example of extremely low streamflow conditions, future efforts to refine the spatial segmentation scheme should also include data from a period of normal streamflow.

V. CHEMICAL VARIABLES

INTRODUCTION

The chemical variables monitored in this program are listed in Table III. These include major chemical forms of four important nutrients (nitrogen, phosphorus, carbon, and silicon). The inorganic form of these nutrients (nitrite (NO2), nitrate (NO3), ammonium (NH4), orthophosphate (PO4), silicate (SiO4)) are necessary for the growth of primary producers such as phytoplankton and submerged aquatic vegetation. The organic forms of these nutrients serve as a nutrient source for the other constituents of the food web such as bacteria, zooplankton, and fish before again being converted back to inorganic forms.

Because these elements are very influential at the base of food web (phytoplankton and bacteria), anthropogenic influences on the cycling of these elements can profoundly impact the aquatic ecosystem. If the natural balance of these nutrients is disturbed, changes can propagate throughout the whole ecosystem. Noxious algal blooms, anoxic waters, fish kills, changes in community species composition, and decreased fisheries harvests are a few of the perturbations that can result. The factors which influence concentrations of these nutrient elements can be grouped into two classes; inputs, and instream cycling. In the following sections each of these elements (N, P, Si, and C) will be briefly discussed with respect to these two influences. Graphical presentations of the data will be used to illustrate processes influencing the nutrient dynamics of each river. Unless otherwise noted, these graphs present the average of surface and bottom samples.

Table V contains information that will be used in discussing inputs. This information has been summarized from a report issued by EPA (Chesapeake Bay Program Technical Studies: A Synthesis, U.S.E.P.A., 1982). For the purposes of this report the inputs have been categorized as municipal, industrial, or fall line. The municipal and industrial categories represent point sources below the fall line. The fall line category represents the nonpoint source inputs from above the fall line as well as any point source inputs above the fall line. Point source inputs above the fall line are relatively minor in relation to nonpoint inputs. It should be noted that this table does not include nonpoint inputs below the fall line.

NITROGEN

Point source inputs of nitrogen originate in both municipal wastewater treatment plants and industrial plants. Some industries can discharge significant amounts of nitrogen, but municipal wastewater treatment plants are the major dischargers of these nutrients. About 75-90% of the nitrogen discharged from municipal sources is in the inorganic forms most available for phytoplankton growth. In the James, discharges from large municipal wastewater treatment plants are responsible for approximately 56% of the total nitrogen input to the river below the fall line. Along the less populated York and Rappahannock Rivers only about 13% of the total nitrogen input is from municipal point sources.

TABLE V

All values are mean daily loads (* 10^3 Lbs/Day)

NITROGEN

JAMES RIVER BASIN

	NO2 + NO3		AMMONIUM		ORGANIC N		TOTAL N	
	INPUT	%	INPUT	%	INPUT	%	INPUT	%
FALL LINE	10.3	59	1.5	4	16	67	29	37
MUNICIPAL	7.2	41	33	90	6	25	44	56
INDUSTRIAL	NA	NA	2.3	6	1.8	8	6	8

YORK/RAPPAHANNOCK RIVER BASINS

	NO2 + NO3		AMMONIUM		ORGANIC N		TOTAL N	
	INPUT	%	INPUT	%	INPUT	%	INPUT	%
FALL LINE	6	95	0.5	38	7	91	9.6	81
MUNICIPAL	0.3	5	0.5	38	0.3	4	1.5	13
INDUSTRIAL	NA	NA	0.3	24	0.4	5	0.8	6

PHOSPHORUS

	JAMES				YORK/RAPPAHANNOCK			
	ORTHOPHOSPHATE		TOTAL PHOSPHORUS		ORTHOPHOSPHATE		TOTAL PHOSPHORUS	
	INPUT	%	INPUT	%	INPUT	%	INPUT	%
FALL LINE	1.6	18	4.5	27	0.34	40	1.1	61
MUNICIPAL	7.2	82	10	61	0.50	60	0.6	33
INDUSTRIAL	NA	NA	2	12	NA	NA	0.1	6

NA : Data not available

Inputs above the fall line account for 37% and 81% of the total nitrogen in the James and York/Rappahannock Rivers respectively. The majority of this comes from nonpoint sources such as surface runoff and groundwater. Nitrate is the form most commonly transported by groundwater because it is very soluble. Though ammonia is also soluble, it will readily adsorb to particles and is usually transported in surface runoff. Storm events are significant factors for organic nitrogen loading due to several reasons. The greatly increased river flow means that a significant amount of organic nitrogen is discharged during storms. Also, much of this nitrogen is particulate organic nitrogen from surface runoff and flushing of small tributaries and wetlands. This particulate organic nitrogen is more biodegradable than the dissolved organic nitrogen that usually comprises the majority of the organic nitrogen pool. While runoff from all types of land use contributes nitrogen, the application of fertilizers and lack of conservation management practices leads to particularly high inputs from agricultural land.

Nitrogen can also be introduced by the atmosphere through rainwater or diffusion of nitrogen gas. Rainwater contains many nitrogen compounds, but the relatively small surface area of rivers generally precludes this as a significant direct input. Certain microbial organisms and some blue-green algae have the ability to utilize nitrogen gas as a nitrogen source through a process called nitrogen fixation. This can be an important localized factor for some nuisance algal blooms, but it is a small factor as far as nitrogen inputs are concerned.

Once the nitrogen has entered the river, it can undergo several biologically and chemically mediated transformations which are important to water quality. The typical nitrogen cycle is its transformation from inorganic to organic form and then back to inorganic form. Ammonium, nitrite, and nitrate are used by primary producers for the production of protein and other organic nitrogen compounds necessary for growth. For phytoplankton, the preferred inorganic nutrient is ammonium, but when concentrations are low they will utilize nitrite or nitrate. As organisms die, decomposition of organic nitrogen compounds produces ammonium and the cycle can then repeat itself.

However, sometimes inorganic nitrogen is utilized for purposes other than incorporation into biomass. Under conditions of excess ammonium, some bacteria will utilize ammonium as an energy source and convert it to nitrite and nitrate. This process is called nitrification and results in consumption of oxygen from the water column. Nitrite concentrations are generally below detection except where nitrification is occurring. Under low oxygen conditions, some bacteria utilize nitrate or nitrite as an oxidizing agent and reduce it to ammonium or gaseous nitrogen. When nitrogen compounds are reduced to gaseous forms, a process called denitrification, the nitrogen can be released to the atmosphere and lost from the aquatic ecosystem. Denitrification is particularly active in estuarine areas and is thought to be largely responsible for the 'nitrogen limitation' in coastal aquatic systems.

There are also many chemical and physical processes which influence nitrogen cycling. Uptake or release of dissolved nutrients from the river sediments is an important factor influencing concentrations in the water column. This can sometimes be driven solely by a concentration gradient, i.e. if concentrations are higher in the water column there will be a loss

into the sediments, likewise, if concentrations are higher in the sediment, there will be a transfer from the sediments to the water column. Low oxygen concentrations in waters close to the sediment surface can also stimulate the release of ammonium from sediments. An oxidized layer at the sediment surface usually inhibits the release of ammonium because it is either adsorbed onto sediments or is oxidized to nitrate. When the sediment surface becomes a reduced environment due to the presence of anoxic water then these processes are not as active and ammonium is released to the water column. Exchanges between the water and sediment can also be activated by changes in pH or oxidation/reduction potential.

PHOSPHORUS

As with nitrogen, the largest point sources of phosphorus are from municipal wastewater treatment plants. In the James river below the fall line point sources account for 61% of the total phosphorus inputs while in the York/Rappahannock rivers, they account for 33% (Table V). Again, as with nitrogen, the biologically important inorganic form (orthophosphate) is the largest fraction of this input and accounts for 70-80% of the total phosphorus input from municipal wastewater plants. Industrial sources account for 11% and 6% of the total inputs from the James and York/Rappahannock rivers respectively. However, information is not available as to what percentage of this is inorganic. Sources above the fall line contribute 27% of the total phosphorus in the James and 61% in the York/Rappahannock. As with nitrogen, the phosphorus inputs above the fall line are largely due to nonpoint sources.

The aquatic phosphorus cycle is generally less complicated than that of nitrogen. Phosphorus is essential in cellular metabolism because of its role in the formation of energy storing enzymes such as ATP (adenosine Tri-phosphate). It is also important in genetic compounds such as DNA and RNA which have sugar-phosphate structural components. The major biological transformation of phosphorus is its uptake by primary producers in the inorganic form (orthophosphate) and its incorporation into an organic form. The organic form is then eventually returned to the inorganic form through biological decomposition. Orthophosphate can also cycle between the particulate form and its dissolved state solely through chemical processes. Under oxygenated conditions dissolved orthophosphate will adsorb to sediments containing metal oxides. Under anoxic conditions, the metal-phosphate compounds break down and the orthophosphate is released. It has also been found that conditions of high pH, such as created during an algal bloom, can cause an orthophosphate release from sediments. In this report orthophosphate includes only the dissolved form of orthophosphate. Particulate phosphorus was calculated as the difference between total phosphorus and dissolved phosphorus and includes both particulate organic phosphorus and orthophosphate adsorbed onto sediment particles.

ORGANIC CARBON

The original study upon which Table V was based did not include carbon. Therefore, no estimates of the importance of various sources can be made here. However, inputs from municipal wastewater treatment plants are significant and these inputs, unlike those of nitrogen and phosphorus,

are regulated to some extent. Some industries such as wood processing plants can also discharge large amounts of carbon. The fall line loading of organic carbon is largely composed of refractory compounds that are relatively resistant to decomposition.

Organic carbon is formed through primary production by organisms such as phytoplankton and submerged aquatic macrophytes. This primary production can be controlled by several factors such as light, temperature, nutrient concentration, toxic compounds, and grazing. Once this organic carbon is created, it serves as an energy and carbon source for other levels of the food web. At each step in the food web oxygen is consumed as the carbon is utilized. The source of oxygen can be dissolved oxygen in the water or inorganic oxidized compounds such as nitrate or sulfate. If too much organic carbon is present its decomposition depletes oxygen from the water column, creating ecological problems.

As with organic nitrogen, high flow events are important in introducing organic carbon into riverine systems. This is because of the large load delivered and also because much of the load is particulate carbon from surface runoff and the flushing of wetlands. This particulate carbon is generally more biodegradable than the dissolved organic carbon that is the largest fraction during base flow conditions.

SILICA

The study upon which Table V is based did not examine silica inputs and to date this nutrient has received relatively little attention. The majority of its input is due to natural weathering of silica minerals. Thus, nonpoint runoff is the major contributor and point sources are generally insignificant.

Silica is a necessary nutrient for the growth of certain phytoplankton. It is taken up in the inorganic form and incorporated into the outer shells of both freshwater and saltwater diatoms. Zooplankton which feed on these phytoplankton have little need for silica and the shells are excreted relatively intact. Optionally, if cells die before being grazed they sink to the sediment surface. The subsequent breakdown into an inorganic form is accomplished mainly through abiotic dissolution. This element is often the limiting nutrient for diatoms and its cycling in relation to that of nitrogen and phosphorus has been suggested to be important in the development of eutrophication related problems. A more complete discussion of these processes as they relate to Virginia tributaries is given in Anderson, G. F. (Estuarine, Coastal and Shelf Science, 1986, Vol. 22, pp. 83-197).

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RAPPAHANNOCK RIVER

Ammonium

It has been estimated that 28% of the ammonium loading to the Rappahannock is from above the fall line with the remainder originating from sources below the fall line (Table V). Concentrations at the fall line ranged from below detection to 0.10 mg/l (Figure 5.1). Longitudinal plots show that seasonally averaged concentrations were generally below 0.15 mg/l throughout the river (Figure 5.2). Municipal point sources are the major input of ammonium below the fall line and most of these are located near Fredericksburg (mile 105). The station closest to these sources is 25 miles down river and because of this distance, the longitudinal plots do not show any indication of the point sources in Fredericksburg. The general pattern observed was similar to that noted for previous years with the exception of somewhat lower concentrations seen in the transition zone (miles 30-50). The spring season had the lowest values at the fall line and yet showed quite high values in the tidal freshwater region. In the summer and fall, concentrations were generally low throughout the river due to high biological uptake, except in the bottom waters of the estuary where ammonium is released from the sediments.

FIGURE 5.1

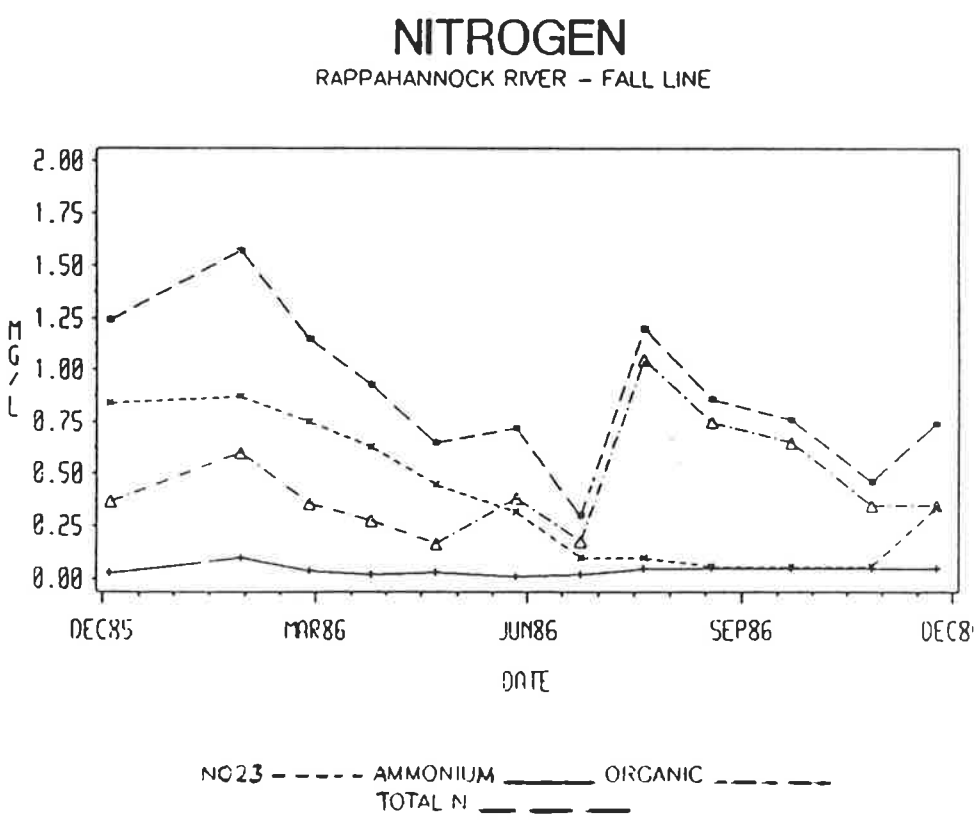
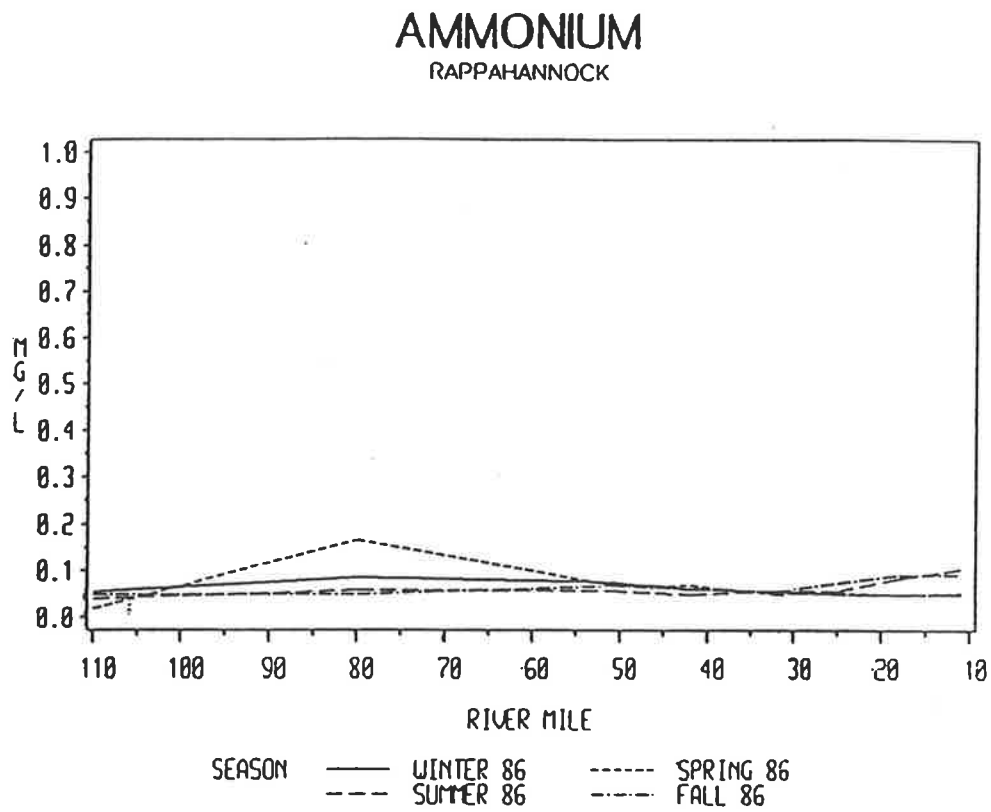


FIGURE 5.2



As discussed on page 31, sediments are a major source of ammonium to the water column. During much of the year, organic nitrogen from the water column is deposited to the sediment where it undergoes decomposition and ammonium is produced. Normally most of this ammonium is converted to oxidized nitrogen (i.e. NO23) or adsorbed to sediment particles. Low concentrations of oxygen slows the normal conversion of the ammonium to oxidized nitrogen. Periods of low oxygen concentrations tend to occur during periods of vertical stratification when there is minimal exchange of water between the surface and bottom layers. This reduction of vertical mixing allows large concentrations of ammonium to accumulate in the bottom waters and upon mixing, this reserve of ammonium can provide a significant amount of nitrogen to the surface water and promote an increase in algal production.

This process is often important as a source of ammonium in the lower Rappahannock River. Longitudinal plots of data from an August 1986 cruise illustrate this process. Dissolved oxygen levels in the bottom waters during this cruise was very low between river miles 10 and 18 while further upriver there was little depletion of oxygen in the bottom waters (Figure 5.3A). In the area of oxygen depletion there were substantially elevated ammonium concentrations in the bottom waters, while ammonium concentrations upriver of mile 18 were below detection (Figure 5.3B).

FIGURE 5.3A
DISSOLVED OXYGEN
RAPPAHANNOCK - CRUISE 44

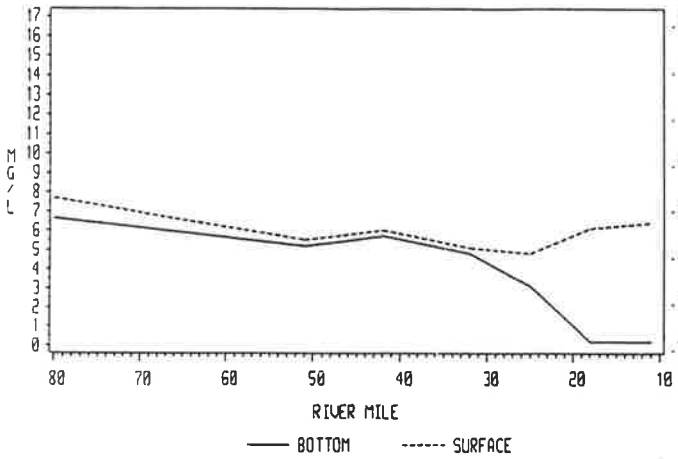
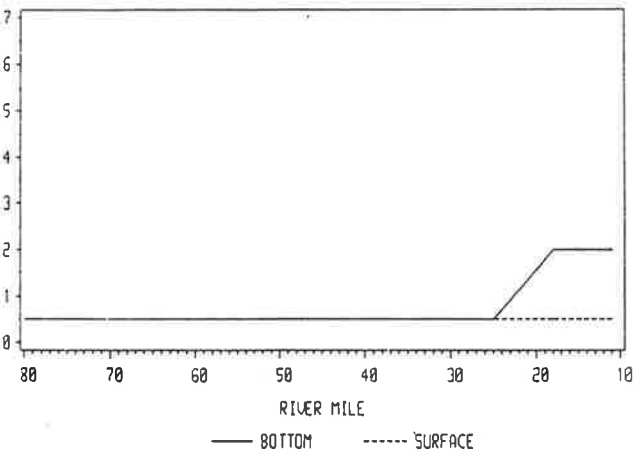


FIGURE 5.3B
AMMONIUM
RAPPAHANNOCK - CRUISE 44



Nitrate plus Nitrite (NO23)

Approximately 95% of the NO23 in the Rappahannock originates from sources above the fall line (Table V). The majority of the input from above the fall line originates from nonpoint runoff as indicated by the elevated concentrations throughout the upper portion of the river during the high streamflow of winter (Figure 5.4). These NO23 concentrations during the winter of 1986 were higher than those observed during 1985. The down river decrease in concentration seen during winter and spring are due to the dilution by estuarine waters which have lower concentrations of NO23. Spring had lower concentrations than winter, and concentrations were lowest throughout the river during summer and fall due to both lower inputs at the fall line, as well as increased biological activity during these seasons.

Organic Nitrogen

About 91% of the organic nitrogen in the Rappahannock originates above the fall line (Table V). Concentrations at the fall line were highest in the months of July through September (Figure 5.1). Below the fall line, the concentration of organic nitrogen reflected the seasonal pattern of phytoplankton production (Figure 5.5). In the winter and spring, concentrations peaked in the estuary (mile 30) where chlorophyll values were highest. Likewise, in the summer and fall, organic nitrogen was highest in the tidal freshwater region (mile 80) where chlorophyll values were also highest during these seasons.

FIGURE 5.4

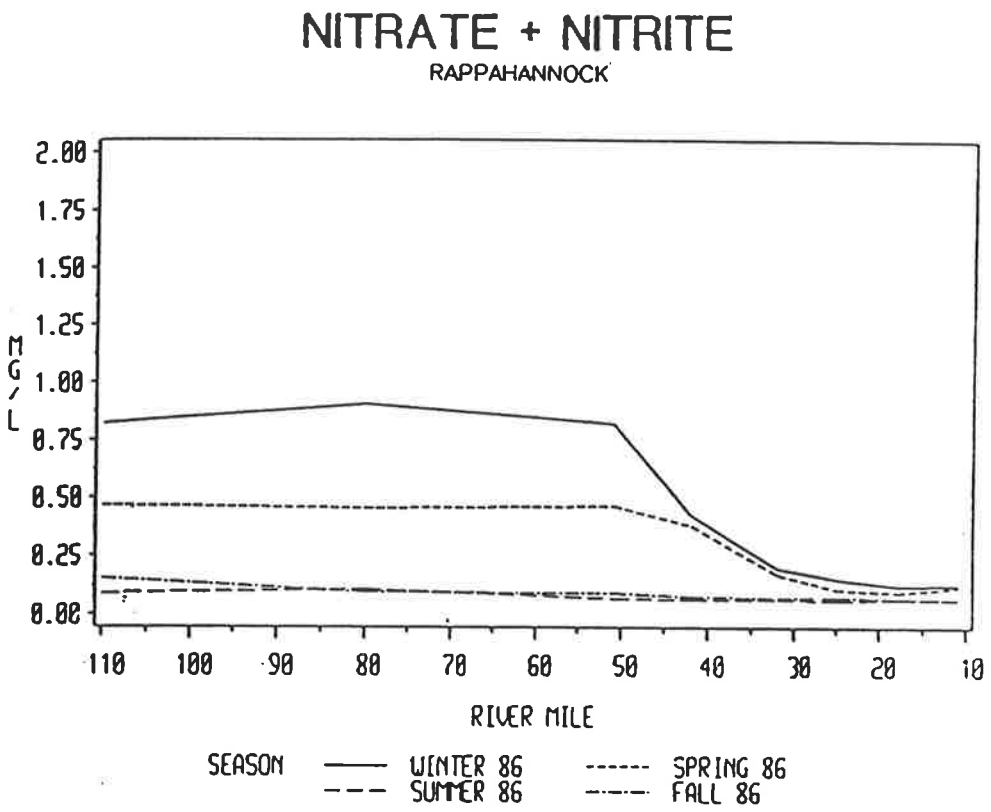
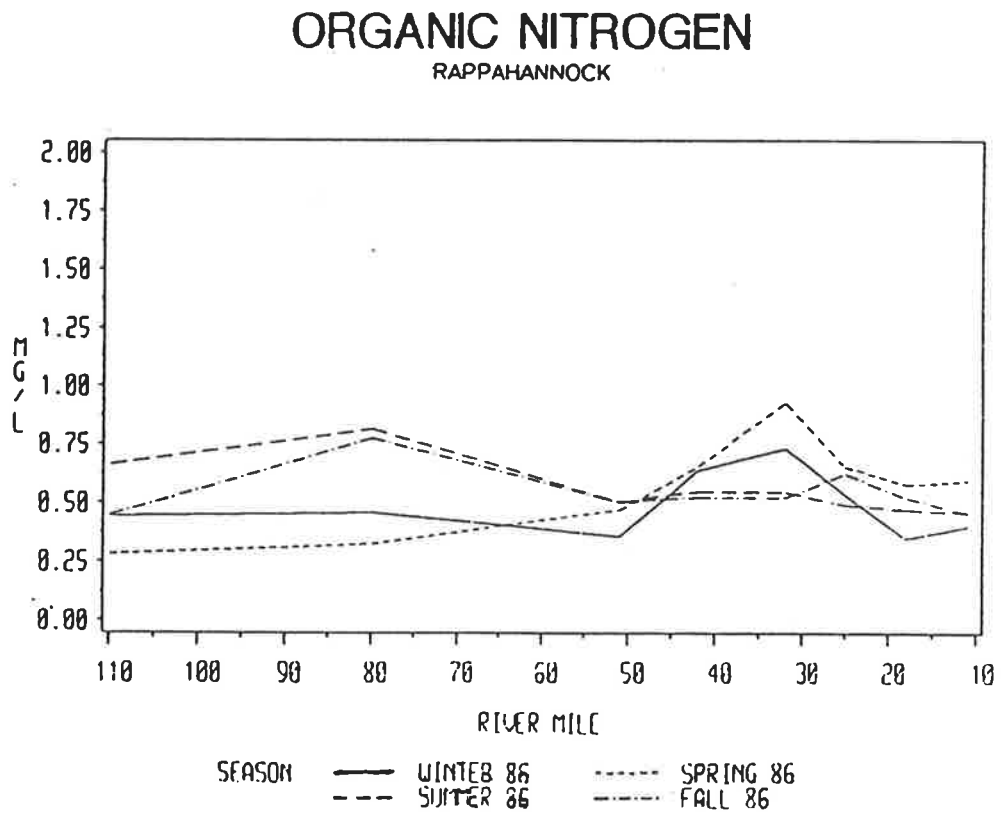


FIGURE 5.5



Total Nitrogen

Approximately 81% of the total nitrogen in the Rappahannock originates above the fall line (Table V). Concentrations at the fall line were quite variable and ranged from 0.27 to 1.7 mg/l (Figure 5.1). During the high streamflow months of winter and spring, the nitrogen input at the fall line was dominated by NO23, while in the summer and fall, the input was mainly organic nitrogen. There were high nitrogen concentrations throughout the upper river during winter due to the high concentration of inorganic nitrogen, while the high nitrogen concentrations in the lower river (miles 20 - 50) during spring were due to high concentrations of organic nitrogen (Figure 5.6). Nitrogen concentrations during summer and fall peaked in the tidal freshwater area and then decreased down river. The peak during these seasons was lower than the peak observed in winter.

The seasonal changes in the contributions of various forms to the total nitrogen pool was the same as observed during previous years. During winter 1986, inorganic nitrogen dominated the freshwater portions of the river (Figure 5.7A). In the estuarine area organic nitrogen increased due to algal production while the inorganic nitrogen decreased due to both uptake by the algae and dilution by estuarine water. During the summer, lower nonpoint input of inorganic nitrogen and increased biological productivity leads to organic nitrogen becoming dominant throughout the river (Figure 5.7B).

FIGURE 5.6

TOTAL NITROGEN

RAPPAHANNOCK

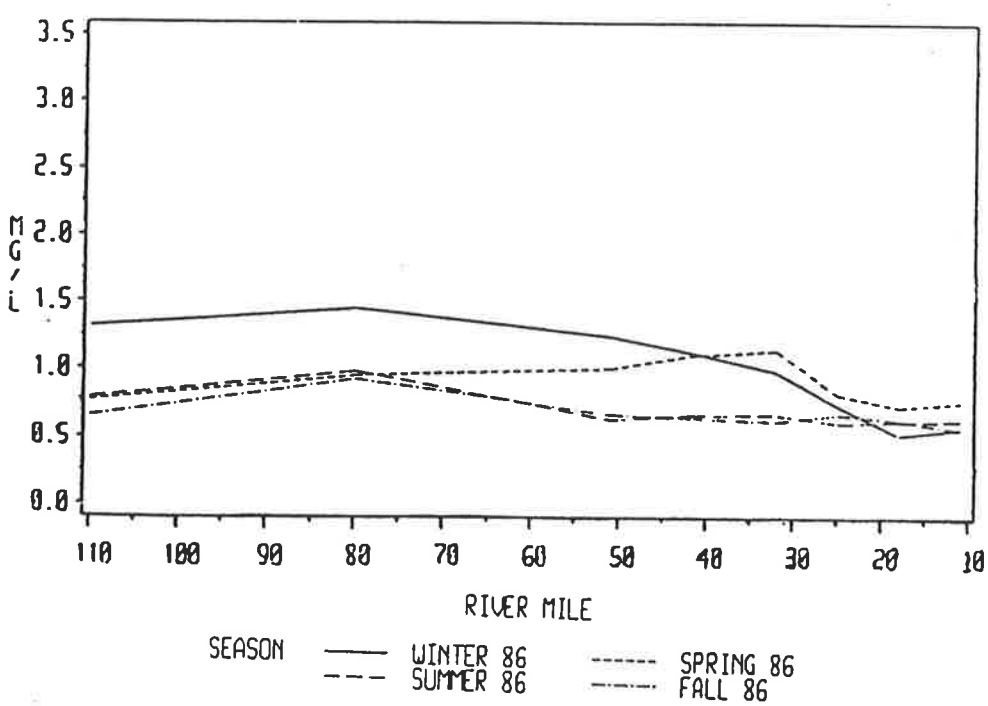


FIGURE 5.7A

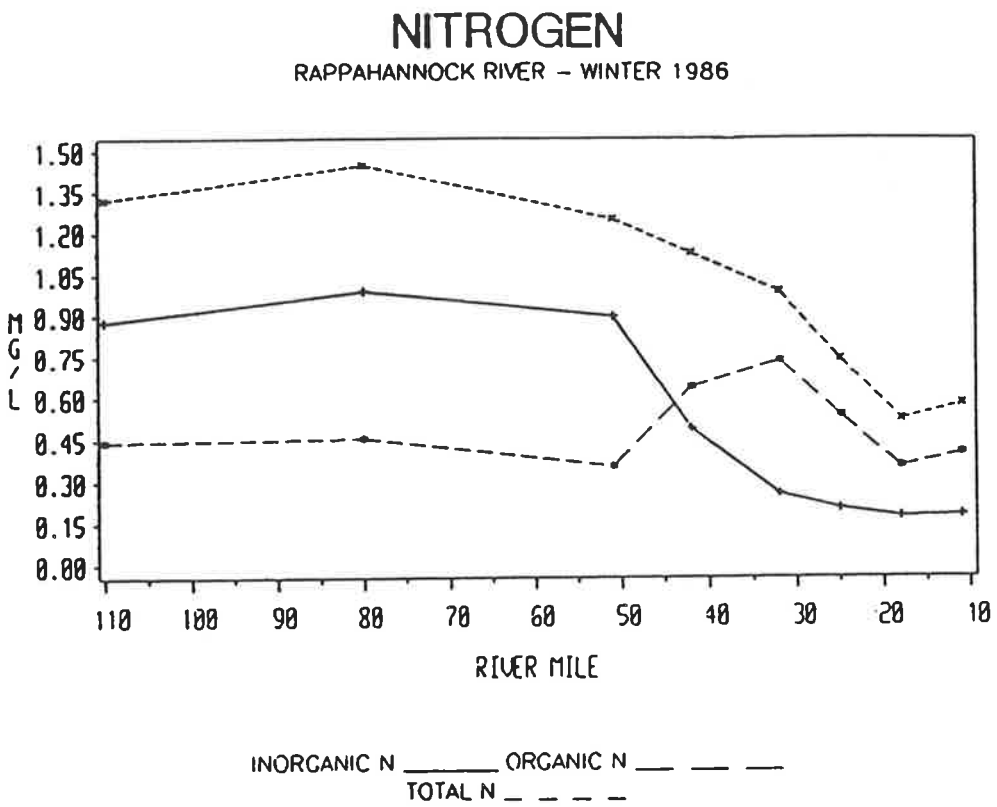
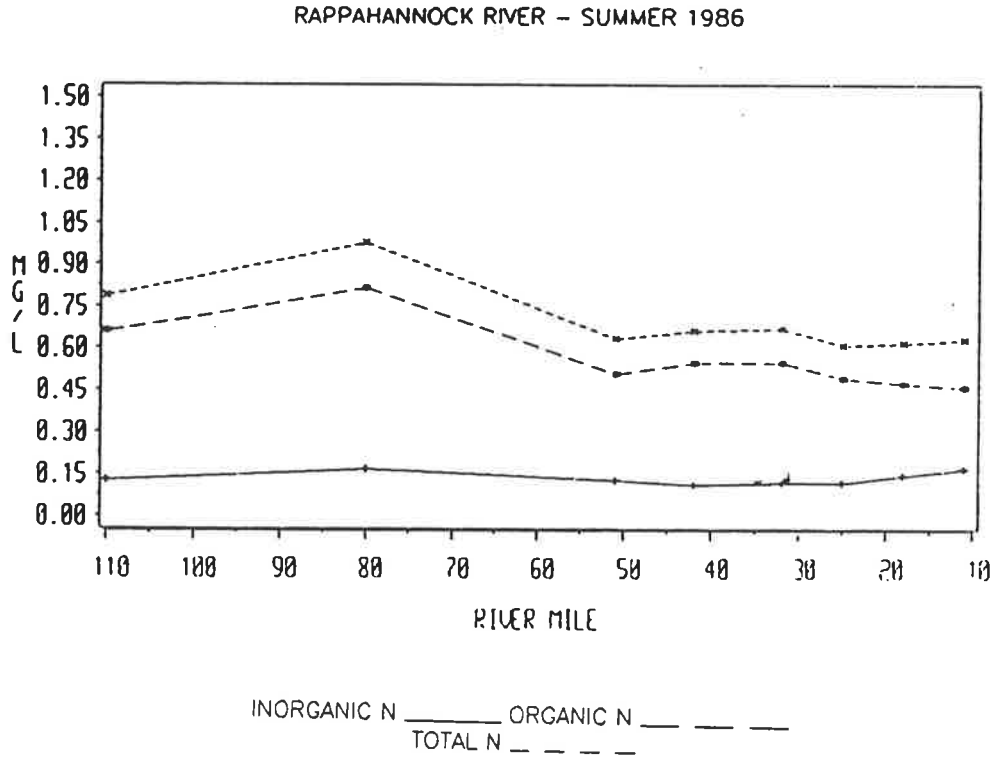


FIGURE 5.7B



PHOSPHORUS

Orthophosphate

Approximately 40% of the orthophosphate loading to the Rappahannock originates above the fall line (Table V). Concentrations at the fall line ranged from below detection to 0.03 mg/l (Figure 5.8). Concentrations were very low throughout the river during all seasons with slightly elevated levels at the fall line during winter due to nonpoint runoff, and slightly elevated levels in the estuary during summer as a result of sediment releases during periods of anoxia. As with ammonium, the influence of point sources in Fredericksburg was not evident because of the distance between the discharges and the nearest monitoring station.

Particulate Phosphorus

Fall line concentrations of particulate phosphorus ranged from below detection to 0.025 mg/l (Figure 5.8). As with organic nitrogen, the longitudinal distribution of particulate phosphorus reflected the seasonal pattern of phytoplankton production (Figure 5.9). In the winter and spring, values were highest in the estuary where chlorophyll values were also high. In the summer and fall, particulate phosphorus concentrations peaked in tidal freshwater, where chlorophyll-a concentrations also peaked. The large peak observed in the transition zone during spring 1985 was not evident in spring 1986.

FIGURE 5.8

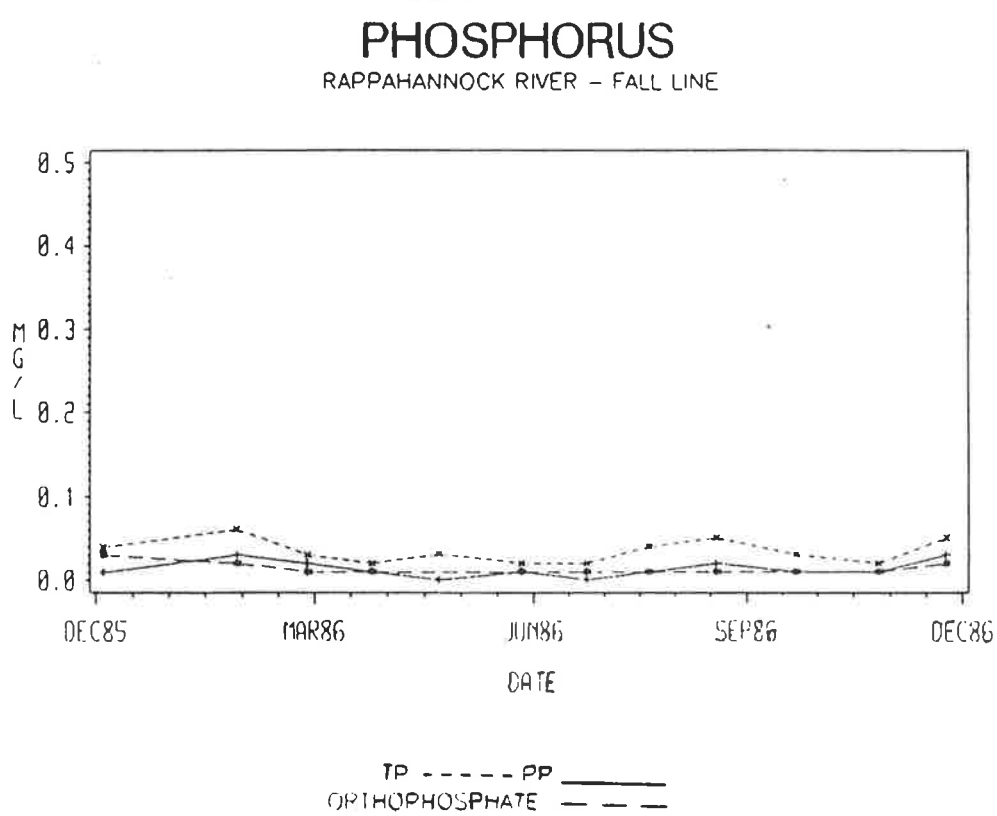
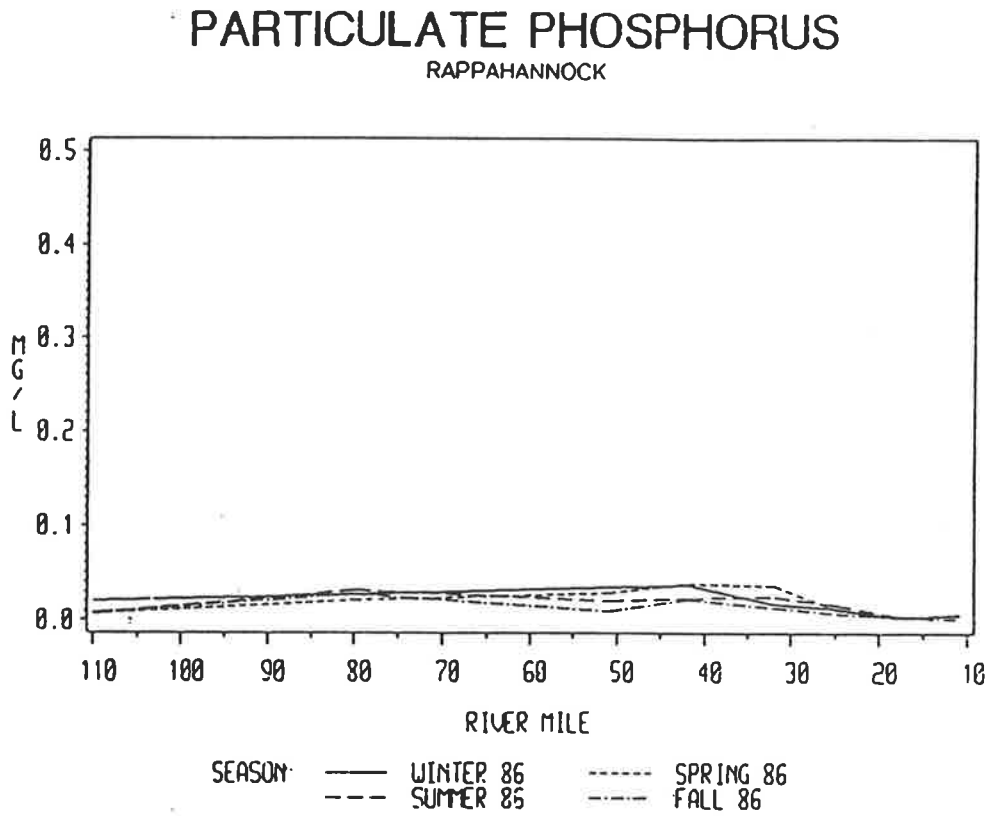


FIGURE 5.9



Total Phosphorus

Approximately 61% of the total phosphorus in the Rappahannock river originates above the fall line (Table V). Most of the time, the fall line input was composed of approximately equal amounts orthophosphate and particulate phosphorus (Figure 5.8). The fall line concentration of phosphorus did not seem to be as high or variable as during 1984-1985. This was probably because of the relative lack of storm events during 1986. The seasonal variability of total phosphorus was the greatest in the transition zone of the river (Figure 5.10). Since total phosphorus in the Rappahannock is composed mainly of particulate phosphorus, the longitudinal distributions are very similar.

ORGANIC CARBON

The seasonally averaged concentrations of organic carbon were similar to those observed in previous monitoring data (Figure 5.11). The fall line exhibited the greatest amount of seasonal variability as well as the lowest average concentrations. Concentrations at the fall line ranged from a seasonal average of 1.70 mg/l during spring to 4.67 mg/l during summer and fall. The highest seasonal averages were always found in the upper estuary/lower transition zone between miles 15 and 45.

FIGURE 5.10

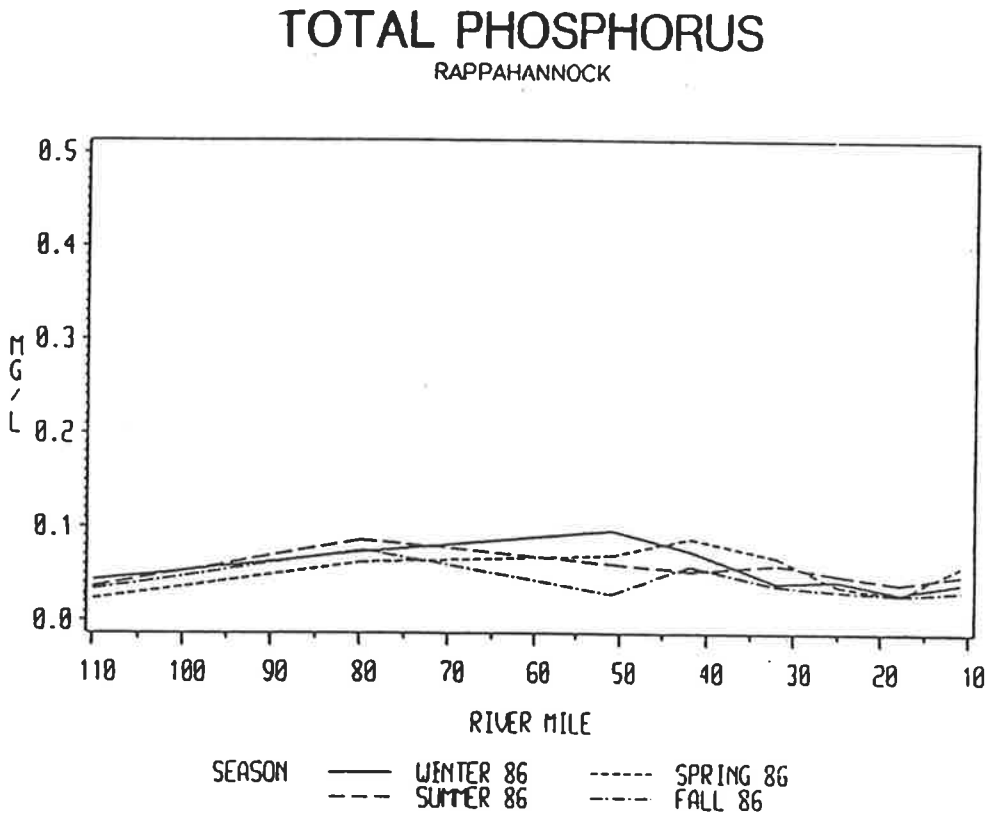
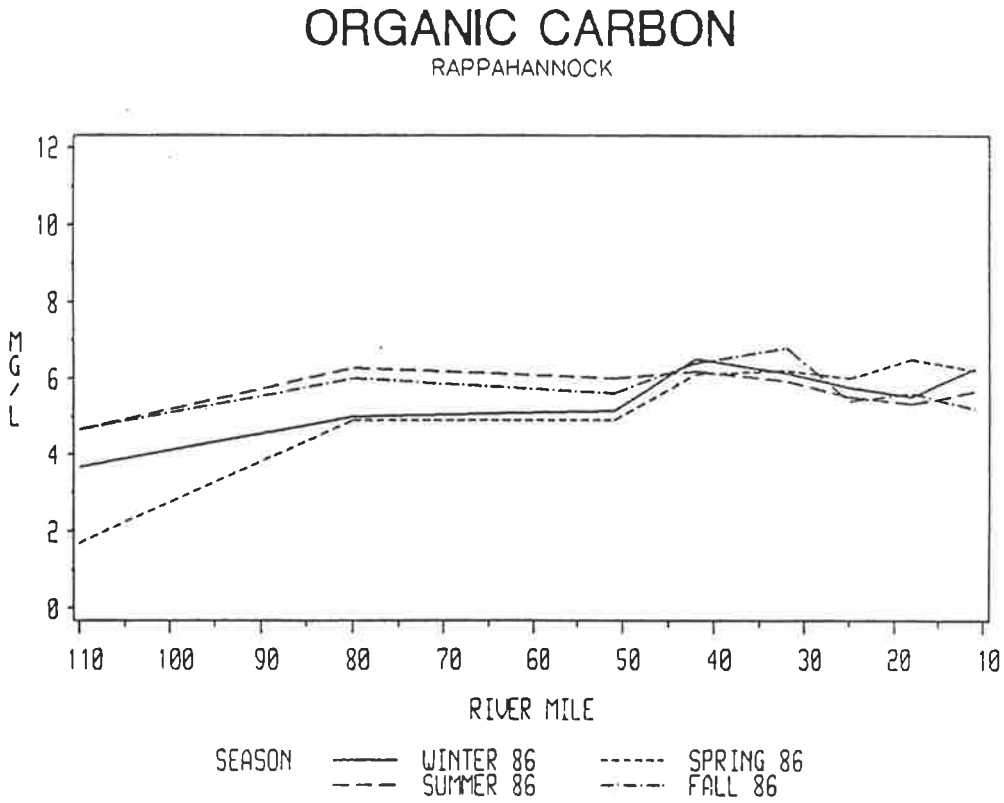


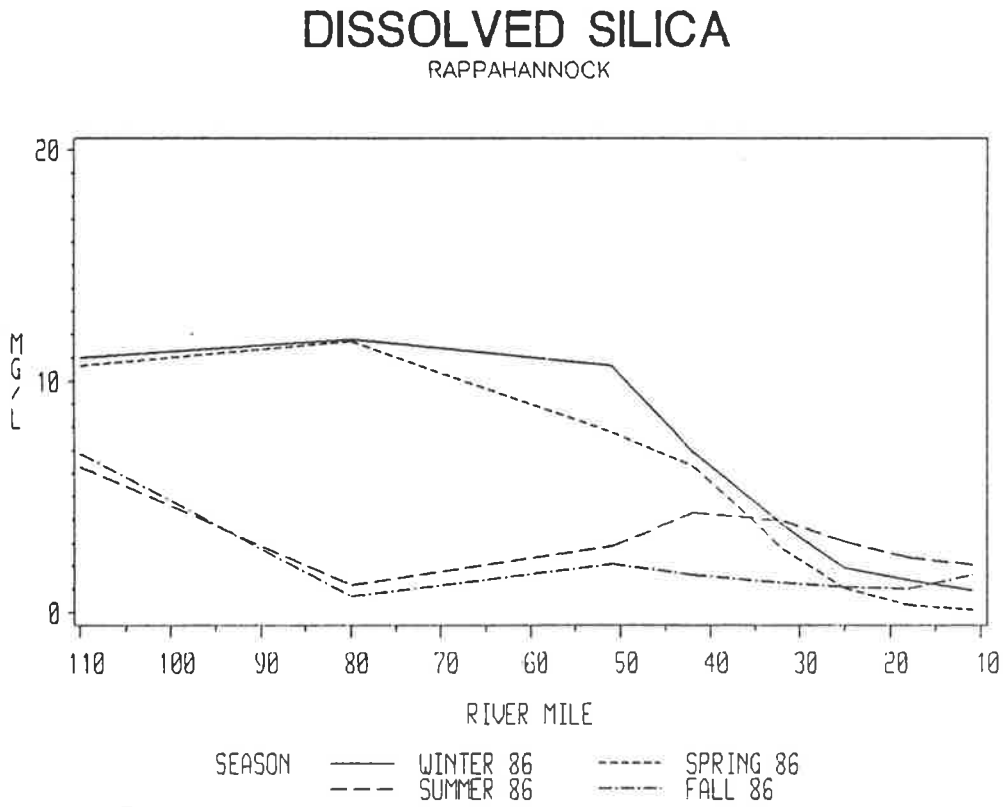
FIGURE 5.11



SILICA

The seasonally averaged concentrations of silicate presented in Figure 5.12 indicate silicate is biologically a very reactive nutrient. During winter, silicate concentrations remained high from the fall line to mile 50 where dilution by estuarine water resulted in a decrease in concentration. In the spring, as temperatures and algal growth increased, the concentrations were still high at the fall line while near mile 80 silicate decreased due to phytoplankton uptake. In the summer and fall, silicate concentrations were lower at the fall line and decreased greatly in tidal freshwater where phytoplankton production was greatest.

FIGURE 5.12



YORK RIVER

NITROGEN

Ammonium

Ammonium loading from above the fall line accounts for 28% of all inputs to the York river (Table V). Concentrations of ammonium at the fall line were often at the limit of detection and reached a maximum of only 0.01 mg/l (Figure 5.13). Progressing down river, there was a peak during winter at the station located just below the confluence of the Mattaponi and Pamunkey rivers (Figure 5.14). At the river mouth, concentrations were slightly elevated during the fall season due to occasional periods of hypoxia and the resultant release of ammonium from sediments. With the exception of these two areas, concentrations were very low throughout the river.

Nitrate plus Nitrite (NO23)

In the York River, 95% of the NO23 loadings originate from sources above the fall line (Table V). Concentrations at the fall line were relatively low, ranging from 0.12 to 0.51 mg/l (Figure 5.13). There was no clear seasonal trend in concentrations at the fall line, but several of the highest values were observed during the summer period.

FIGURE 5.13

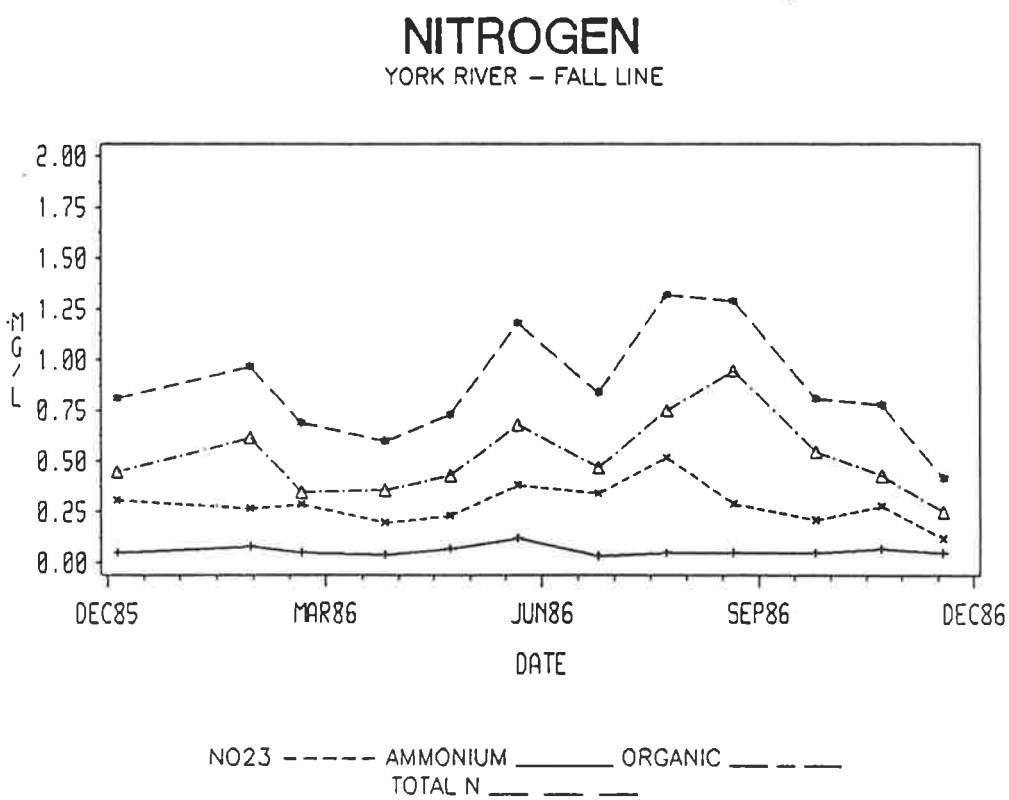
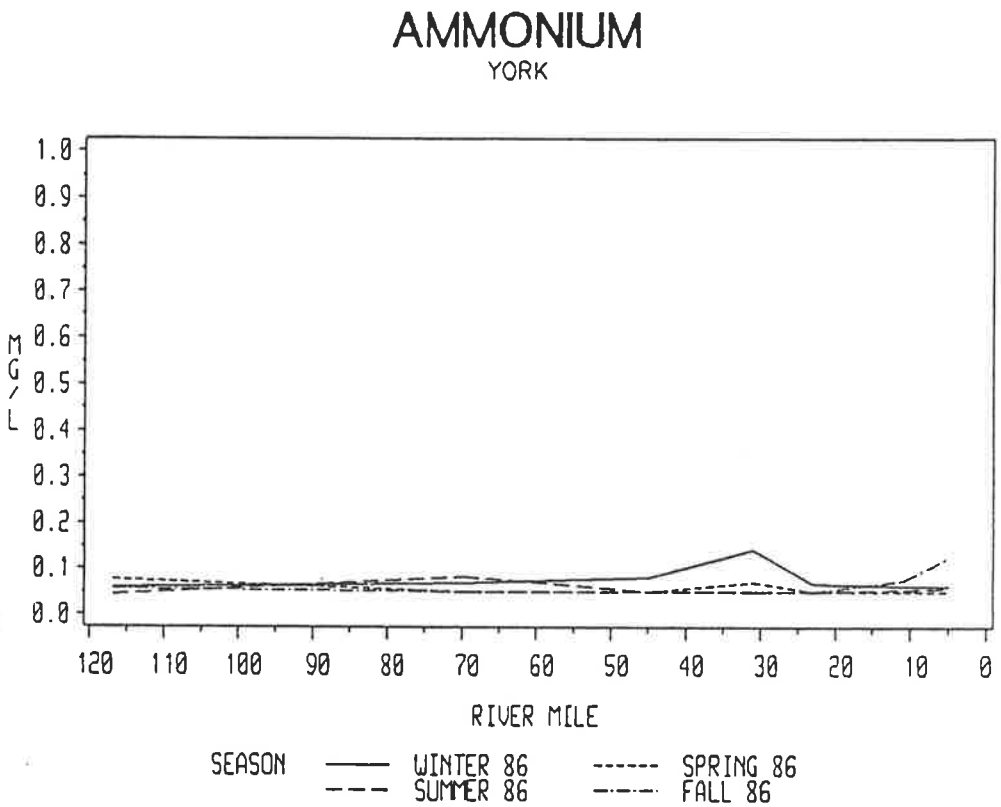
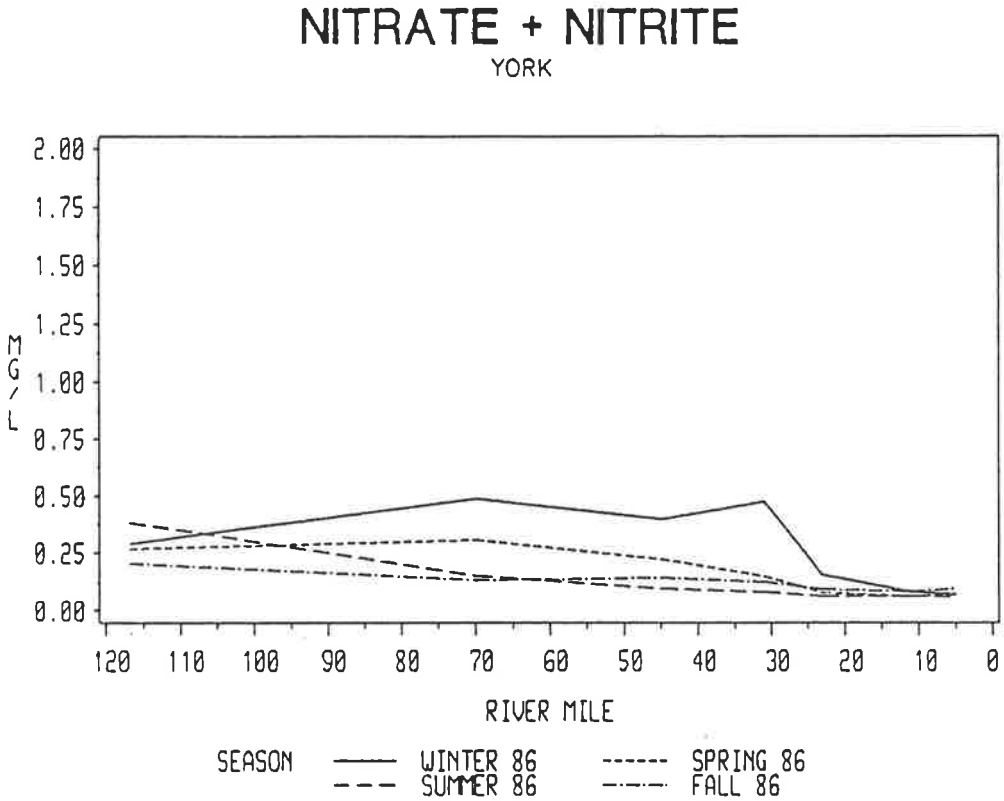


FIGURE 5.14



Throughout the river, nitrite is a very minor component of the NO23, except during hypoxic periods in the estuary (Figure 5.15). Nitrite was undetectable in the tidal freshwater zone over 95 percent of the time, but the estuary had undetectable nitrite concentrations only 67 percent of the time. While the fall line and estuary concentrations of NO23 were relatively stable, there were seasonal differences in the tidal freshwater and transition zones. There was a definite increase in NO23 concentration in tidal freshwater (miles 70 - 30) during the winter (Figure 5.15). The same increase was observed during 1985, and as in the Rappahannock, it was higher in 1986 than during 1985. This peak may be the result of both increased inputs from the extensive tidal marshes in this area and lowered biological uptake during the colder months. During the warmer seasons of summer and fall, a decrease in concentrations occurred in tidal freshwater due to uptake by both the tidal marshes and phytoplankton. During the growing seasons marshes tend to retain inorganic nutrients, while during colder months inorganic nutrients are lost to the river. The estuary (miles 5 - 20) had consistently low NO23 concentrations because of the dilution by high salinity Bay water, which typically has low NO23 concentrations.

FIGURE 5.15

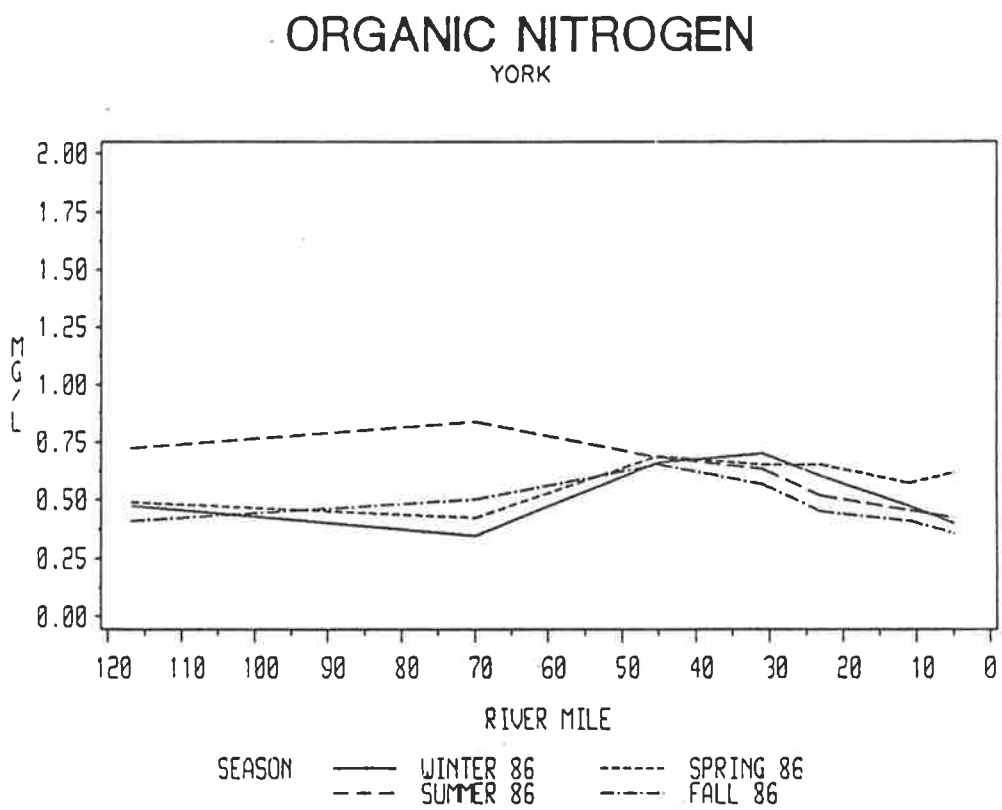


Organic Nitrogen

Sources above the fall line account for 91% of the organic nitrogen loadings to the York (Table V). The peaks observed during May and August at the fall line were during high flow events, indicating that nonpoint sources provide most of the input above the fall line.

At the fall line, the average summer concentration of organic nitrogen was 0.73 mg/l. This average was higher than the other seasons, which averaged less than 0.50 mg/l (Figure 5.16). During the summer, organic nitrogen remained high throughout much of the river, then decreased to 0.43 mg/l near the river mouth. The other seasons exhibited a peak in organic nitrogen in the transition zone (miles 25 - 45) and then decreased toward the river mouth. Input from the tidal marshes along the river probably contribute much of this organic nitrogen. There are also discharges from a kraft paper mill near the mouth of the Pamunkey which may contribute to the increase in organic nitrogen.

FIGURE 5.16



Total Nitrogen

Approximately 81% of the total nitrogen loading to the York originates above the fall line (Table V). Due to very low inorganic nitrogen concentrations, the nitrogen pool in the York is usually dominated by organic nitrogen. At the fall line, organic nitrogen concentrations can be several times higher than inorganic nitrogen. Thus the seasonally averaged distribution of total nitrogen is very similar to that of organic nitrogen. As observed in 1984-1985, there were two main seasonal patterns of nitrogen evident in the York River. In the winter, nonpoint runoff is higher and biological activity is lower. This results in increased inorganic nitrogen concentrations and low organic nitrogen concentrations (Figure 5.17A). Total nitrogen concentrations peaked in the transition zone and then decreased toward the river mouth. In the warmer months, biological activity transforms inorganic nitrogen to organic nitrogen causing organic nitrogen to become the dominate form of nitrogen (Figure 5.17B). This pattern was particularly pronounced in the tidal freshwater area of the river, while the estuary was dominated by organic nitrogen year around.

FIGURE 5.17A

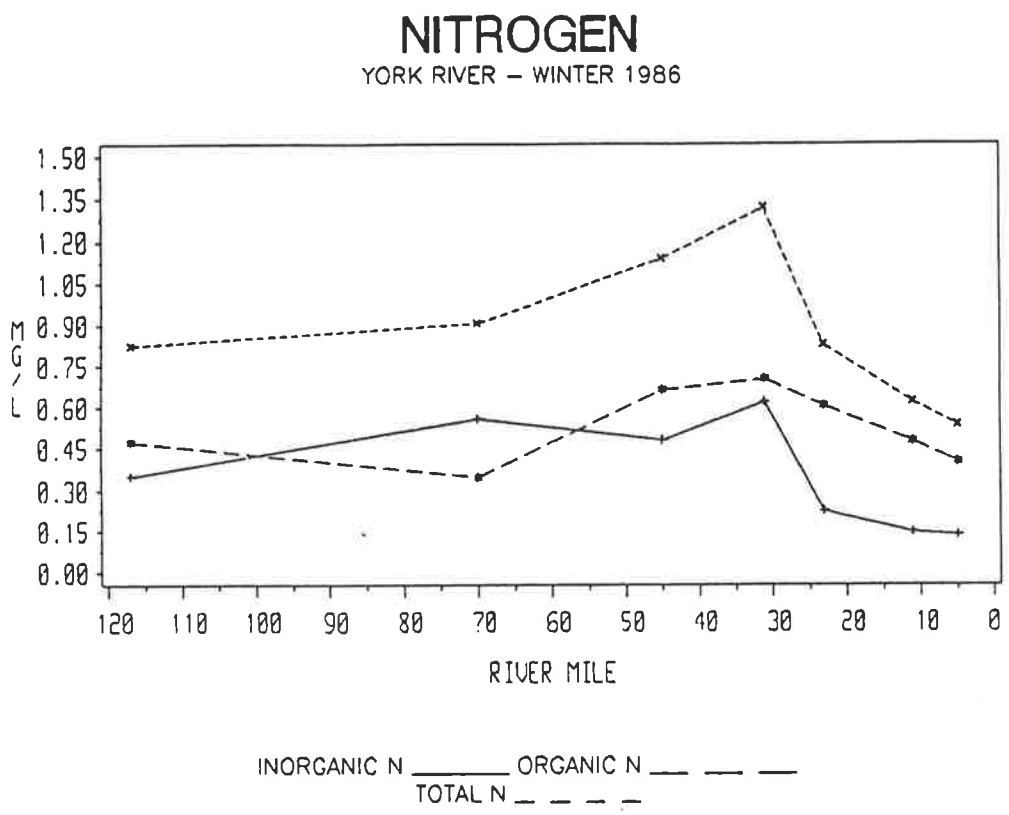
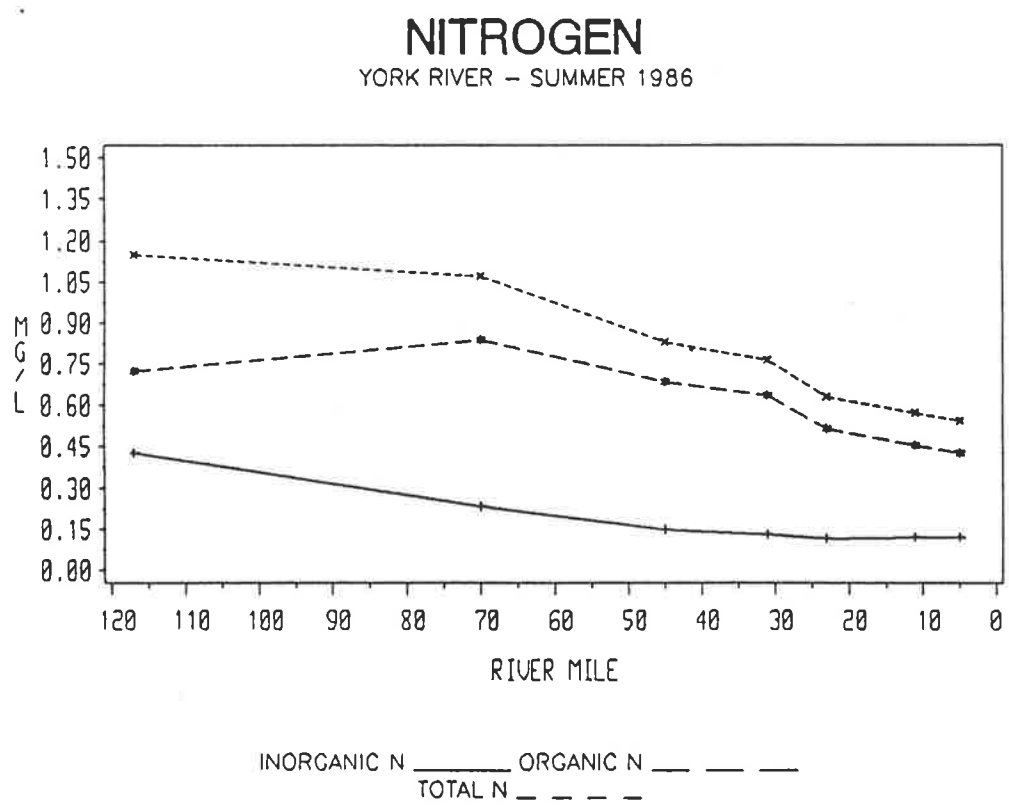


FIGURE 5.17B



PHOSPHORUS

Orthophosphate

In the York River, approximately 40% of the orthophosphate loading originates above the fall line (Table V). Concentrations at the fall line ranged from below detection to 0.12 mg/l (Figure 5.18). Concentrations at the fall line had the greatest amount of seasonal variability. The tidal freshwater portion of the river (miles 40 - 70) had the lowest concentrations of orthophosphate and least amount of seasonal variability (Figure 5.19). In the estuary, orthophosphate concentrations were low in the winter and spring due to uptake by phytoplankton, and elevated during summer and fall probably as a result of sediment release.

Particulate Phosphorus

The concentration of particulate phosphorus at the fall line ranged from 0.01 to 0.13 mg/l (Figure 5.18). Several of the peak concentrations occurred during or after high streamflow events. Most of the particulate phosphorus was probably inorganic orthophosphate adsorbed to sediment particles. The combination of high streamflows and high concentrations results in a significant amount of the annual loading occurring during high flow events.

The seasonally averaged down river concentration of particulate phosphorus is depicted in Figure 5.20. As in previous monitoring reports, a very distinct feature is the peak in concentration at mile 45, near the

FIGURE 5.18

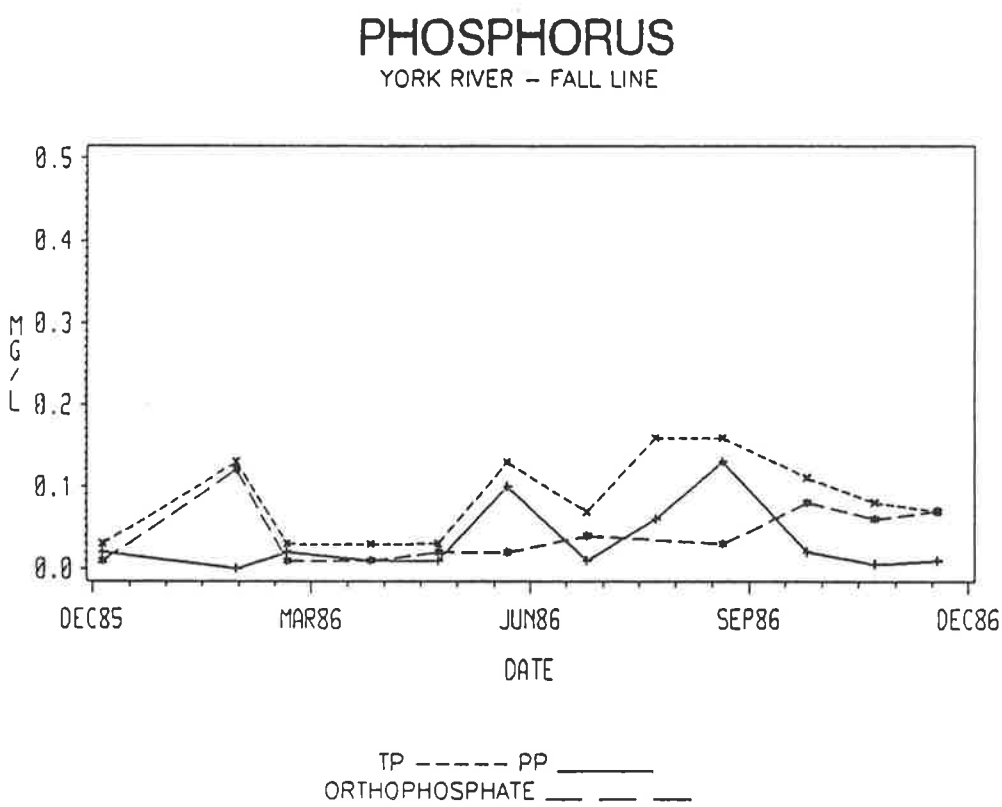


FIGURE 5.19

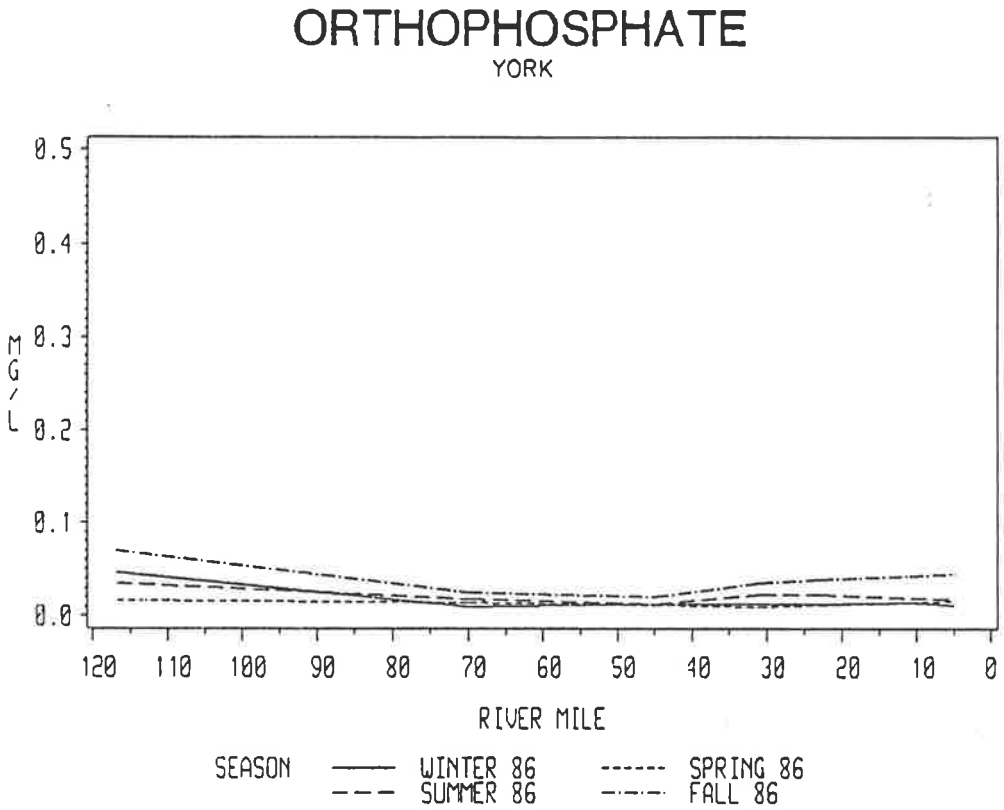
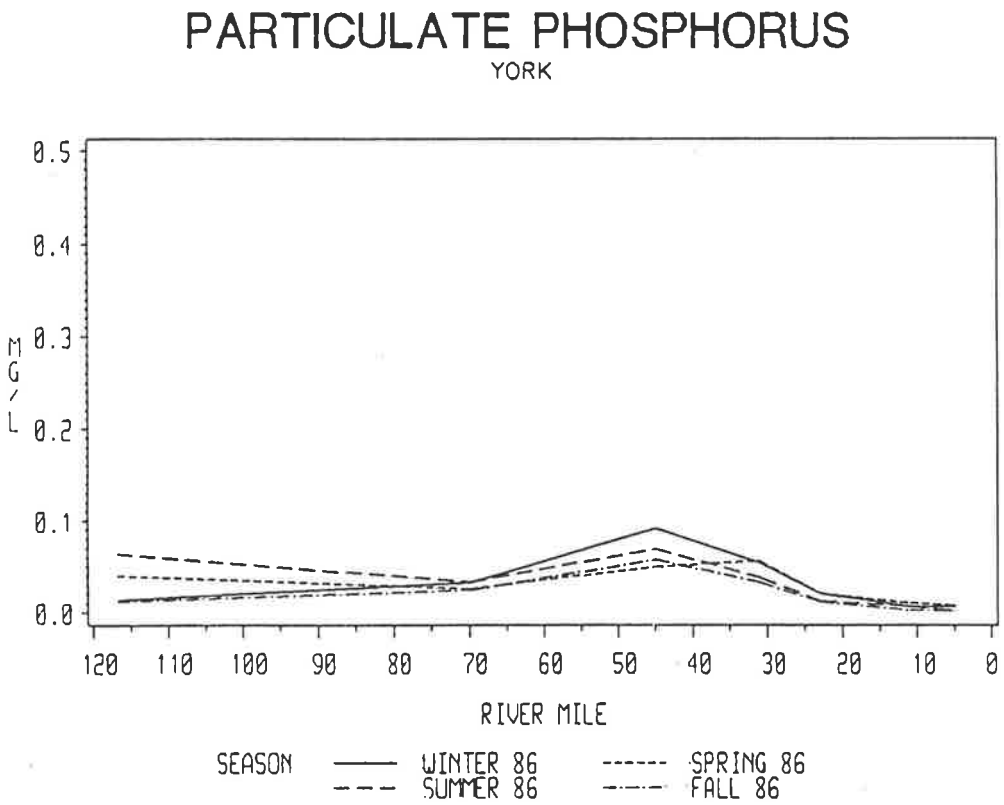


FIGURE 5.20



upriver limit of saltwater intrusion. Though this peak in particulate phosphorus occurred in the turbidity maximum where sediment concentrations are high, the occurrence of high organic nitrogen and carbon at the same location suggests that this peak is also a response to a large input of organic matter. This station is located just upstream of the confluence of the York and the Pamunkey rivers. The Pamunkey has very extensive marshes along its border and undoubtedly some of the organic production of these marshes contributes to the peak in particulate phosphorus. Some of this organic matter may also be a result of discharges from the kraft paper mill located in West Point.

Total Phosphorus

It has been estimated that 61% of the phosphorus input to the York comes from above the fall line (Table V). Concentrations at the fall line ranged from 0.03 to 0.16 mg/l (Figure 5.18). During much of the low flow periods, dissolved orthophosphate was the dominant form passing across the fall line. However, because of the large loads of particulate phosphorus delivered during storm events, particulate phosphorus probably accounts for the largest fraction of the annual phosphorus load. As stated above, much of this particulate phosphorus is orthophosphate adsorbed to sediment particles.

Longitudinal profiles of phosphorus concentration during the spring and the fall illustrate some of the similarities and differences between seasons (Figure 5.21A&B). During the high flow period of spring, the

FIGURE 5.21A

PHOSPHORUS

YORK RIVER - SPRING 1986

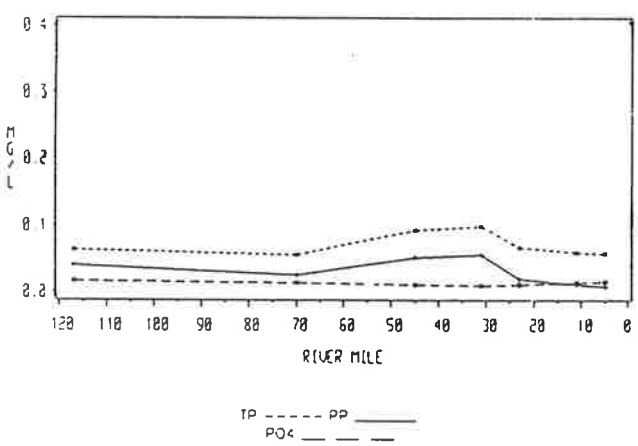
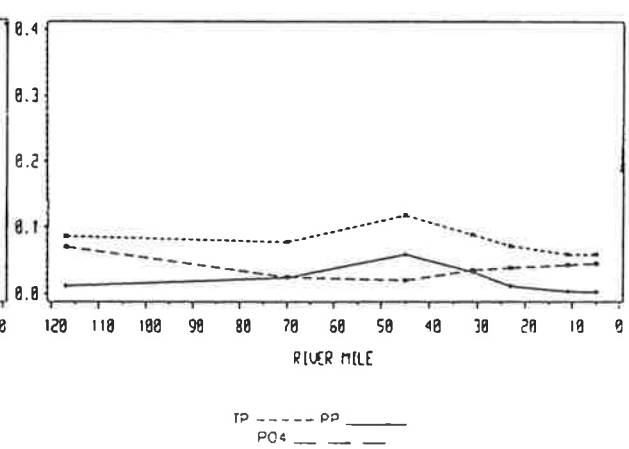


FIGURE 5.21B

PHOSPHORUS

YORK RIVER - FALL 1986



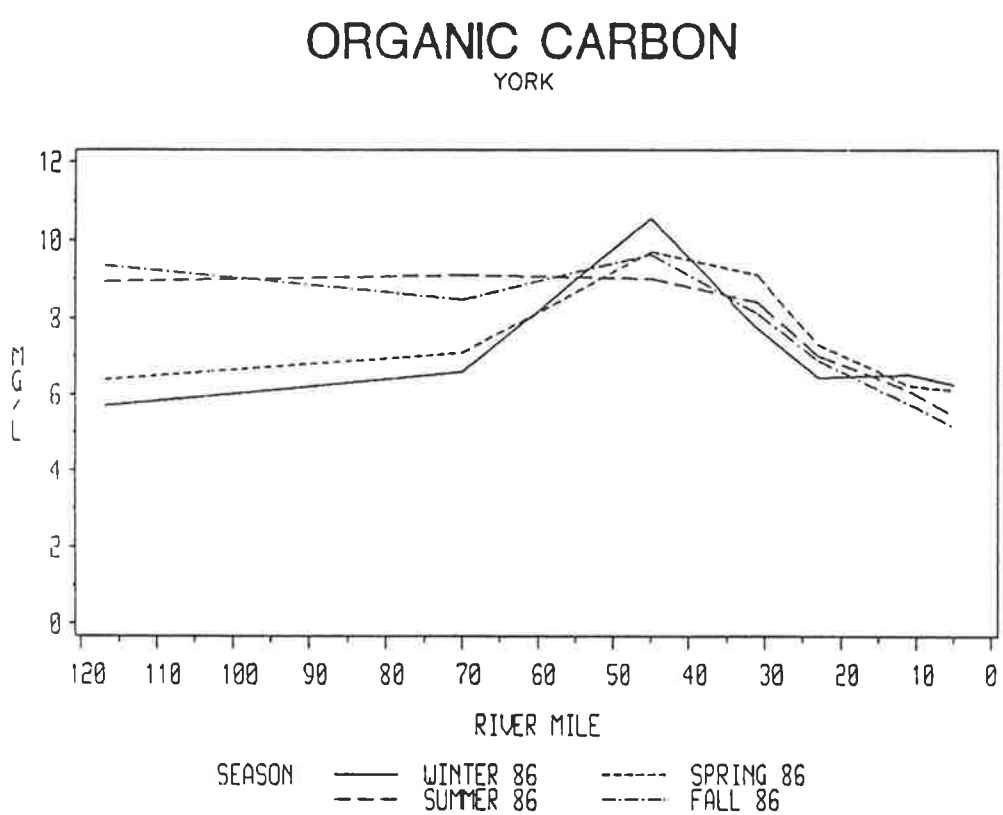
phosphorus at the fall line is mainly particulate due to the nonpoint runoff of sediments and the increased turbulence during high flow which keeps particulate material suspended in the water column. Because the streamflow during the fall is mainly contributed by groundwater input and the river is flowing slower, the input at the fall line is largely dissolved forms (i.e. orthophosphate) and particulates tend to settle out of the water column. In the transition zone (mile 30-50), there is always a peak of particulate phosphorus due both to inputs of organic materials and the presence of the turbidity maximum, where particulate materials are concentrated.

In the estuary (miles 0-20), particulate and dissolved phosphorus are both low during the spring, but in the fall, orthophosphate levels are relatively high. This is a result of the increased frequency of hypoxia which develops in the fall and triggers the release of orthophosphate from the sediments.

ORGANIC CARBON

Concentrations of organic carbon at the fall line were quite variable and ranged from 4.60 to 11.0 mg/l (Figure 5.22). During summer and fall concentrations were high at the fall line and remained high through the tidal freshwater and transition areas until declining in the estuary. Winter and spring had much lower concentrations at the fall line and tidal freshwater stations, peaked in the transition zone, and then decreased in the estuary.

FIGURE 5.22

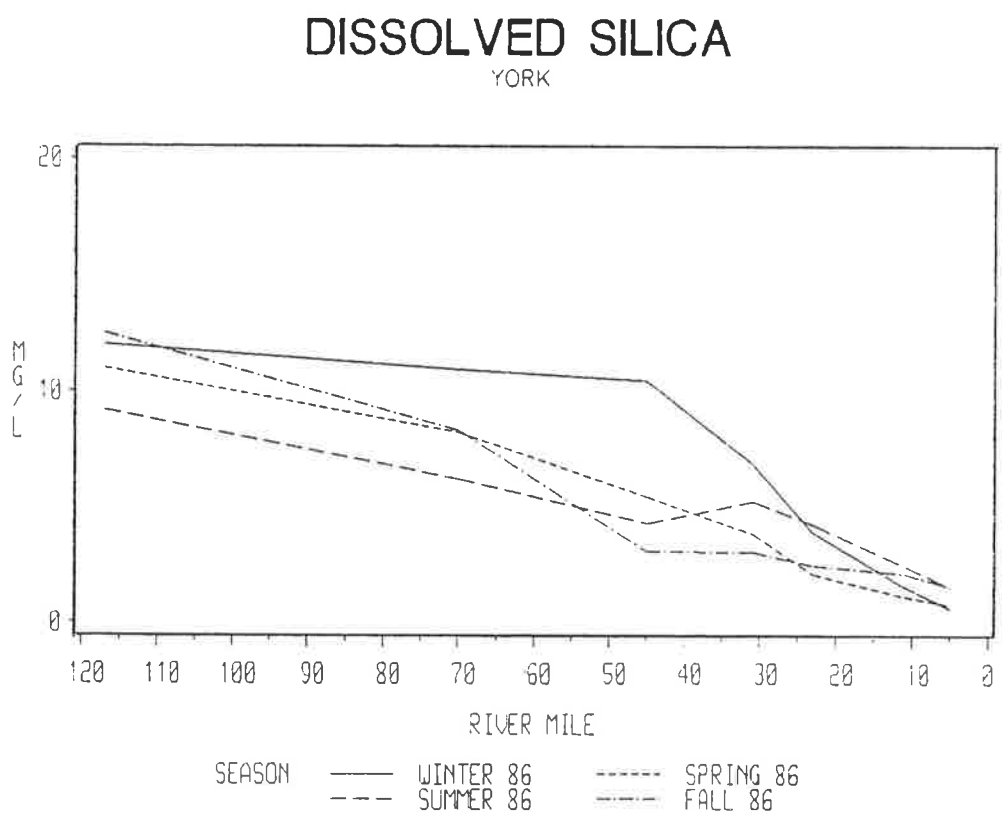


The organic carbon peak in the transition zone corresponded with elevated concentrations of organic nitrogen and particulate phosphorus. As speculated with organic nitrogen, the elevated level may be a function of the tidal wetlands or discharges from the kraft paper mill in West Point. As the river water flows down through the estuarine stations and mixes with Chesapeake Bay water, this organic matter is diluted and the concentration declines.

SILICA

The fall line concentration of silica ranged from 7.2 to 14.5 mg/l. Seasonally averaged concentrations throughout the river are depicted in Figure 5.23. During the winter, silica concentrations were high from the upper river to mile 45, which was the upriver extent of saltwater intrusion, then decreased down river due to estuarine dilution. The other seasons, particularly summer and fall, exhibit a decrease in silicate concentrations in the transition zone due to uptake by phytoplankton. Down river from this area silicate increased during the summer as a result of recycling of particulate silicate previously taken up by phytoplankton.

FIGURE 5.23



JAMES RIVER

NITROGEN

Ammonium

Because of the large point source discharges to the tidal James, only about 4% of the ammonium inputs to the James originate above the fall line (Table V). The concentration of ammonium at the fall line ranged from below detection to 0.05 mg/l (Figure 5.24). Municipal point sources are estimated to contribute 90% of the ammonium loading to the James, thus having a great influence on the distribution of ammonium within the river. As seen in Table VI, ammonia concentrations sometimes were above the recommended instream criteria adopted by the VWCB. Ammonium exhibited a consistent peak in concentration at mile 99, between Richmond and Hopewell (Figure 5.25). A majority of the observations above the criteria were at mile 99. The low streamflows of summer and fall resulted in higher instream concentrations and more observations above the criteria than during the winter or spring. High streamflow and lower biological activity during the winter resulted in the displacement of the peak down river, yet even during winter the ammonia criteria was occasionally violated. The subsequent decline in concentration in the estuary is due to a combination of algal uptake, dilution, and nitrification. The James River Water Quality Monitoring Program (JRWQMP), with its more spatially intensive sampling, located the peak in ammonium at mile 103, below the Richmond area wastewater treatment plants.

FIGURE 5.24

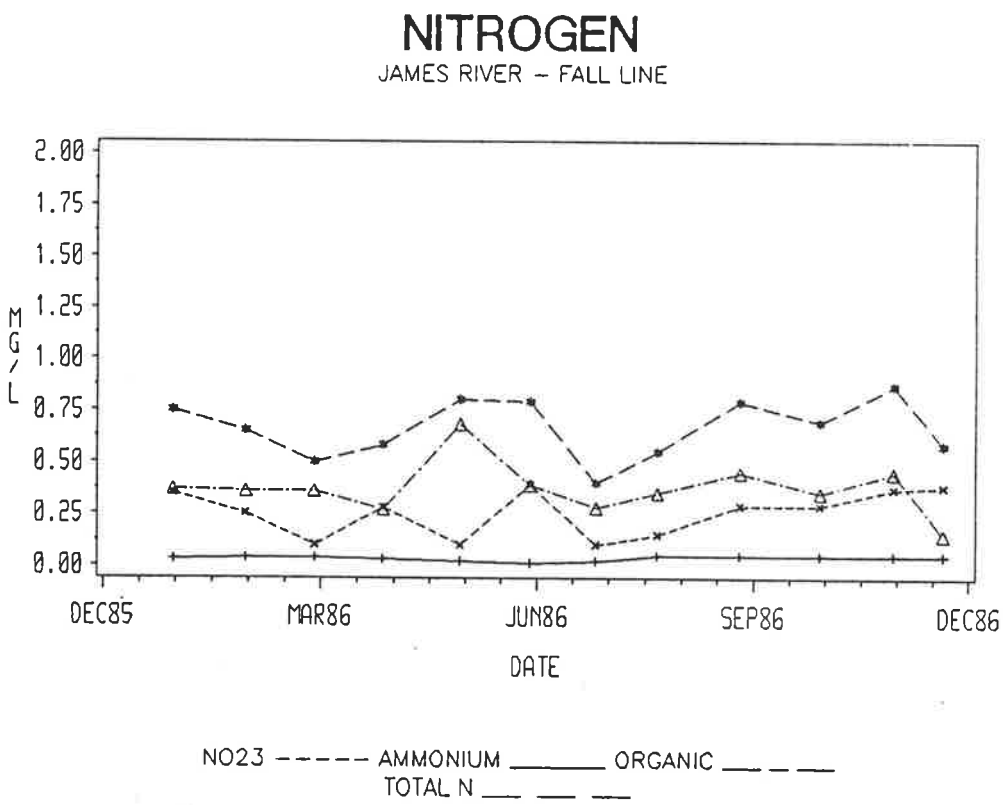


TABLE VI

OBSERVATIONS ABOVE THE AMMONIA CRITERIA - 1986

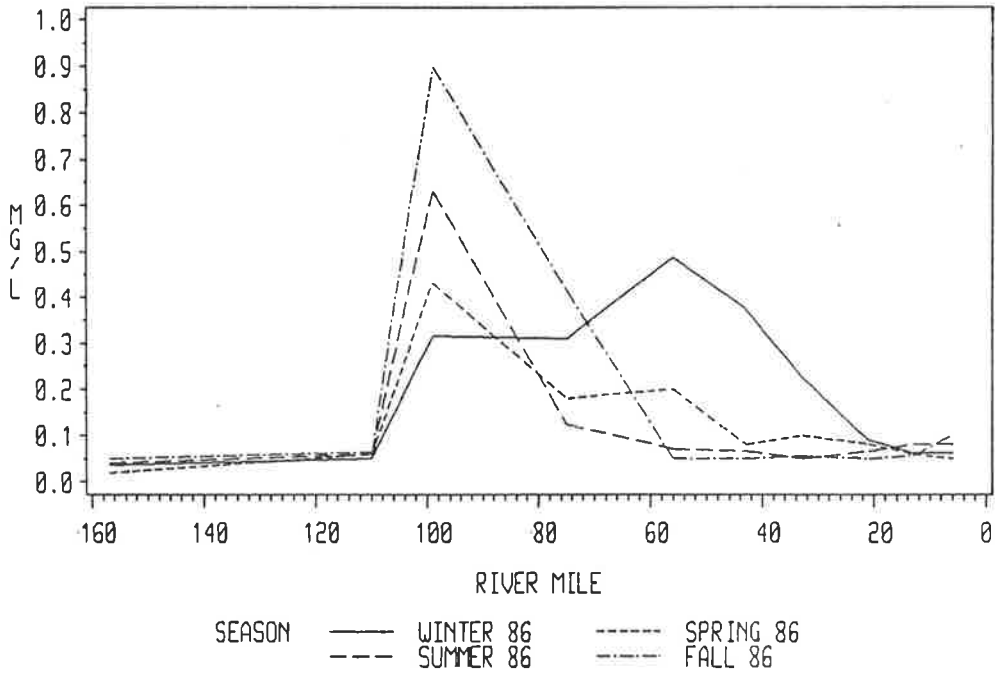
STATION	DEPTH	DATE	AMMONIA *	CRITERIA *
TF5.3	SURFACE	MARCH 28	0.40	0.34
TF5.3	BOTTOM	MARCH 28	0.40	0.23
TF5.3	SURFACE	JUNE 24	0.80	0.73
TF5.3	SURFACE	AUGUST 6	0.80	0.73
TF5.3	SURFACE	SEPT. 23	1.20	0.83
TF5.3	BOTTOM	SEPT. 23	1.20	0.65
TF5.3	SURFACE	OCT. 7	1.30	1.00
TF5.3	BOTTOM	OCT. 7	1.20	1.00
TF5.4	SURFACE	AUGUST 6	0.60	0.14
TF5.5	SURFACE	NOV. 25	1.20	1.10
TF5.6	SURFACE	DEC. 22	0.80	0.35
TF5.6	BOTTOM	DEC. 22	0.70	0.52

* mg/l as total ammonia (ammonium + un-ionized ammonia)

FIGURE 5.25

AMMONIUM

JAMES



Nitrate plus Nitrite (NO23)

According to Table V, the fall line load of NO23 accounts for 59% of the total input. Concentrations at the fall line ranged from 0.10 to 0.38 mg/l (Figure 5.24).

The down river distribution of NO23 indicated a marked increase in the tidal freshwater and upper transition zones of the river (Figure 5.26). The maximum seasonal average of 1.45 mg/l, observed in the fall of 1986, was much higher than in previous reporting periods. These elevated levels are followed by a decrease in the estuary due to dilution by Bay water as well as biological uptake. As with ammonium, there is a down river shift of the peak during the winter. These peaks are a result of instream nitrification of ammonium and to a lesser extent the point source discharge of NO23. The variable location of these peaks result from a complex relationship between inputs, river flow, and biological processing.

Figure 5.27 illustrates the process of nitrification in the James during summer 1986. The peak of ammonium at mile 99 reflects inputs from Richmond area municipal dischargers. Down river a decline in ammonium and a peak in nitrite are evident, reflecting the first step of nitrification (oxidation of NH4 to NO2). Further down river nitrite decreases and nitrate peaks, which indicates the second step of nitrification (oxidation and NO2 to NO3). For every 1 mg of ammonium that undergoes the process of nitrification, 4.6 mg of oxygen are utilized. therefore, nitrification is a major oxygen consuming process and thus an important factor impacting the water quality of the upper tidal James.

FIGURE 5.26

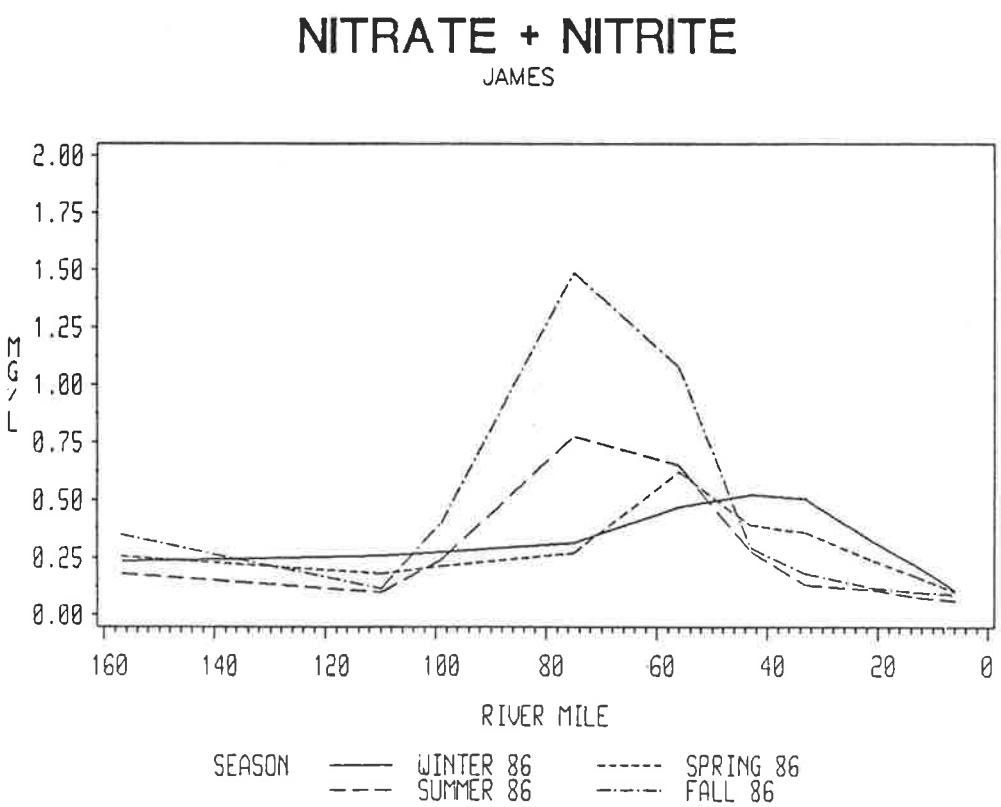
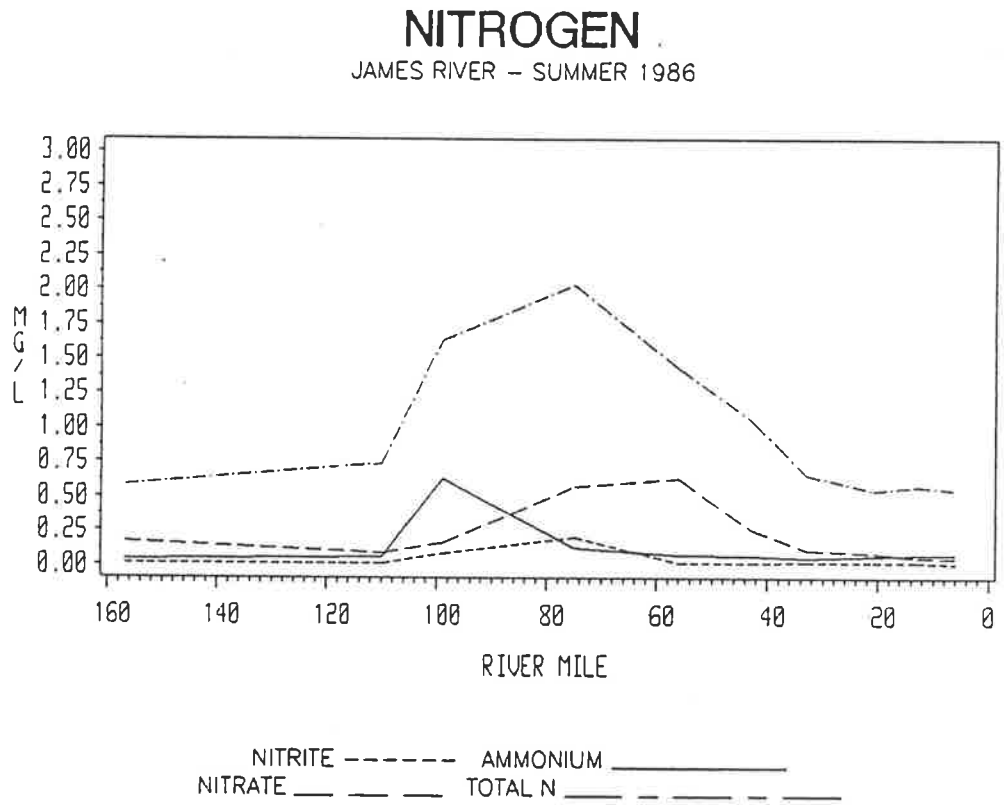


FIGURE 5.27

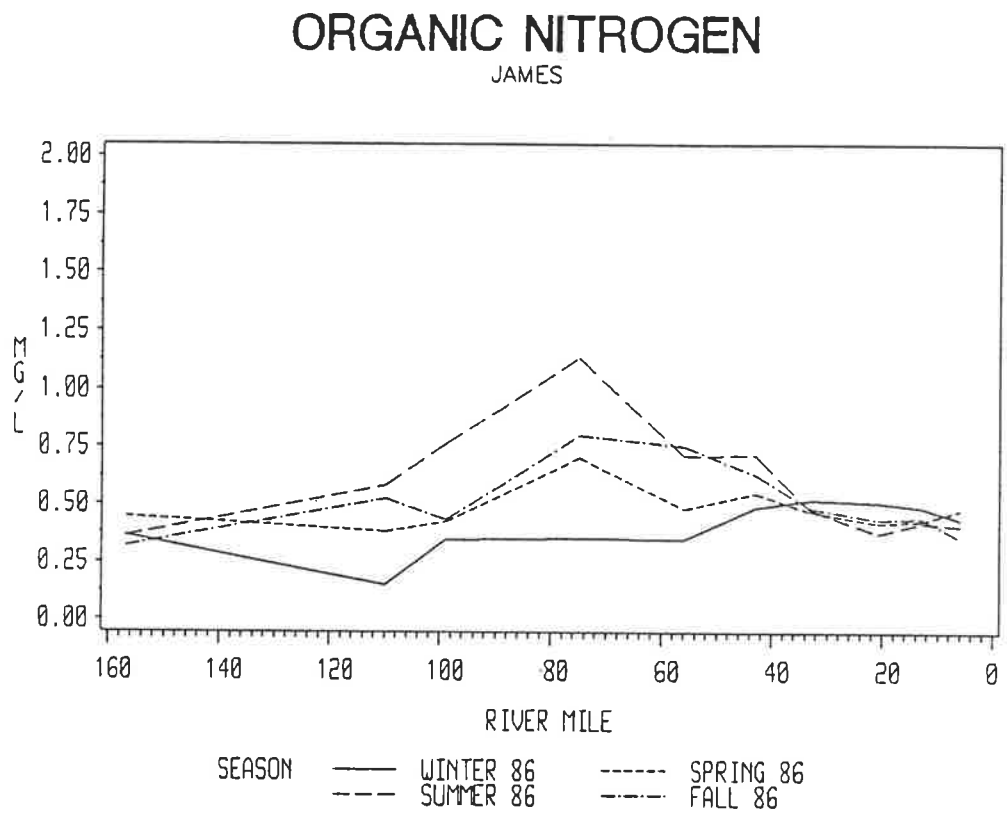


Organic Nitrogen

Fall line input of organic nitrogen accounts for 67% of the total input to the James river (Table V). Concentrations at the fall line ranged from 0.20 to 0.70 mg/l (Figure 5.24).

Figure 5.28 depicts the seasonally averaged concentration throughout the river. At the fall line, there was little difference between seasons. In the tidal freshwater and transition zones, there was a great amount of variability between seasons as well as between stations. Concentrations in these areas were much higher during summer than winter. Municipal and industrial sources, which account for 33% of the organic nitrogen loading to the James, are partially responsible for the increase. Some of the increase is also due to algal production in this region, as well as input from the Appomattox. In the estuary there was less variability, with the highest seasonal concentration occuring in winter.

FIGURE 5.28



Total Nitrogen

Fall line input accounts for 37% of the total nitrogen input to the James (Table V). Concentrations at the fall line ranged from 0.40 to 0.80 mg/l (Figure 5.24). On the majority of dates the major form of nitrogen was organic.

Progressing down river, a large increase in total nitrogen occurs in the Richmond/Hopewell area (Figure 5.29). It has been estimated that 64% of the total nitrogen loading below the fall line of the James comes from point sources, much of which occurs in this region. The high streamflow of winter and spring acted to shift this peak further down river than during other seasons. The peaks observed during the summer and fall of 1986 were higher than those during the same seasons of 1984 and 1985, probably a reflection of the more extensive drought conditions during the latter part of 1986.

The nitrogen distribution in the James varied between seasons as a result of changes in streamflow and biological utilization. The distribution of nitrogen during winter and summer are depicted in Figures 5.30A and 5.30B, respectively. During most seasons the dominate form of nitrogen at the fall line is organic. In the tidal freshwater area, inorganic nitrogen was the dominate form of nitrogen during the winter and fall. During the spring and summer organic and inorganic nitrogen exhibited comparable concentrations in the tidal freshwater area. Further down river in the estuary, inorganic nitrogen decreases rapidly and organic nitrogen becomes the dominant form during all seasons.

FIGURE 5.29

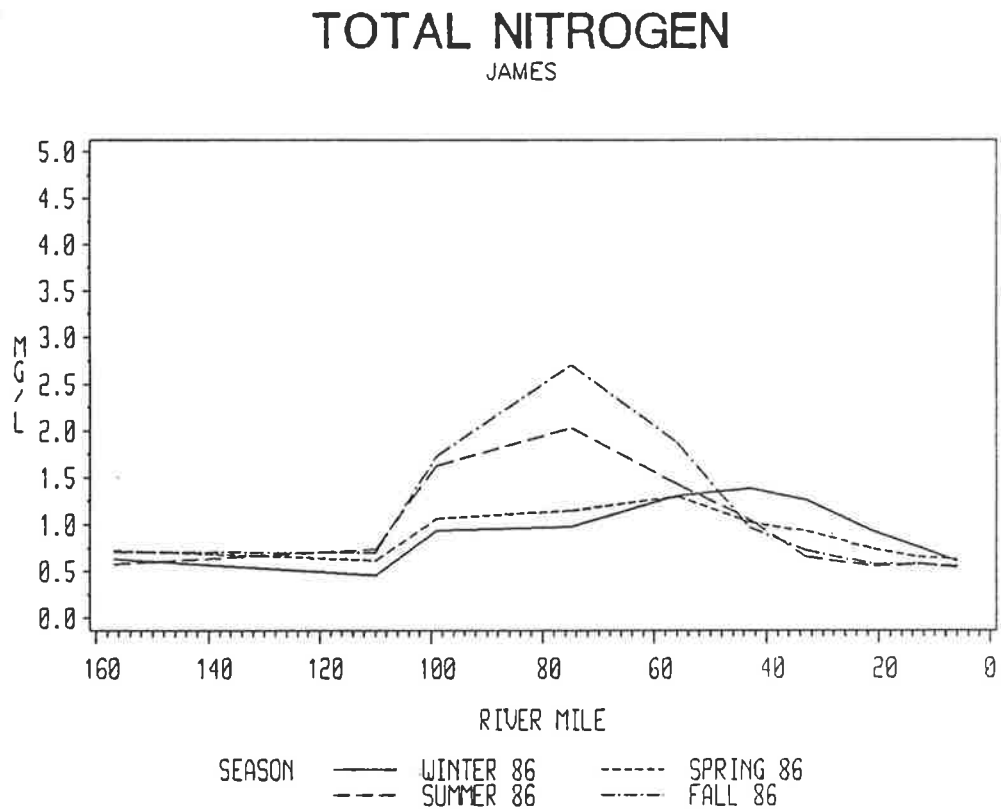


FIGURE 5.30A

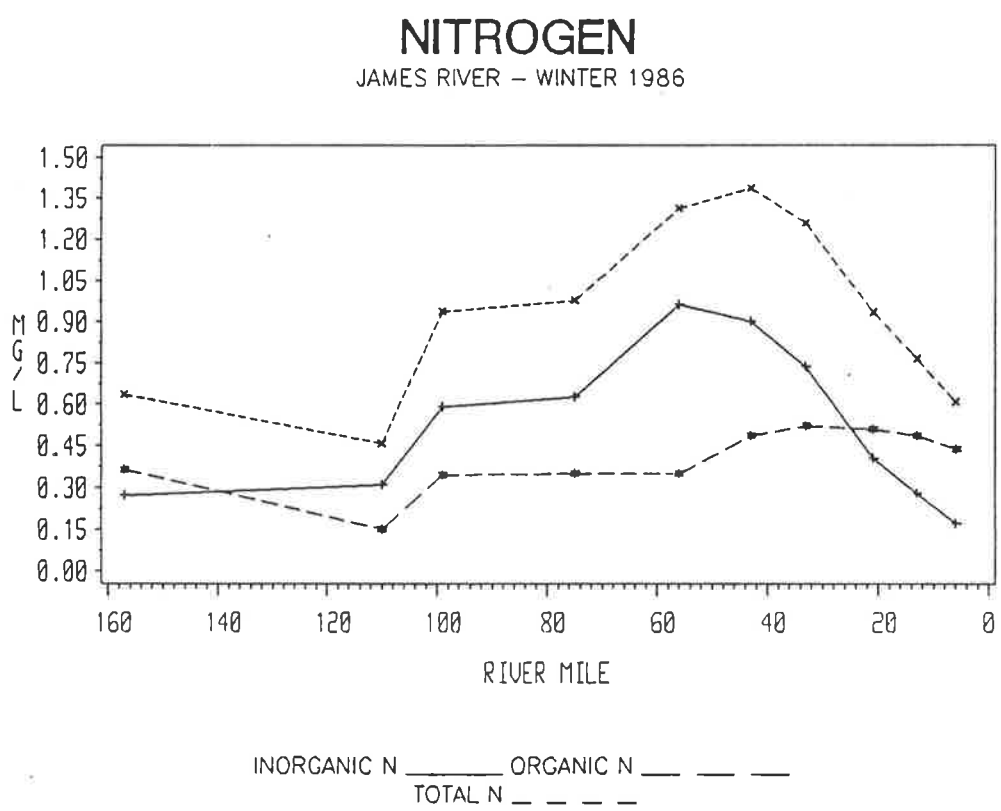
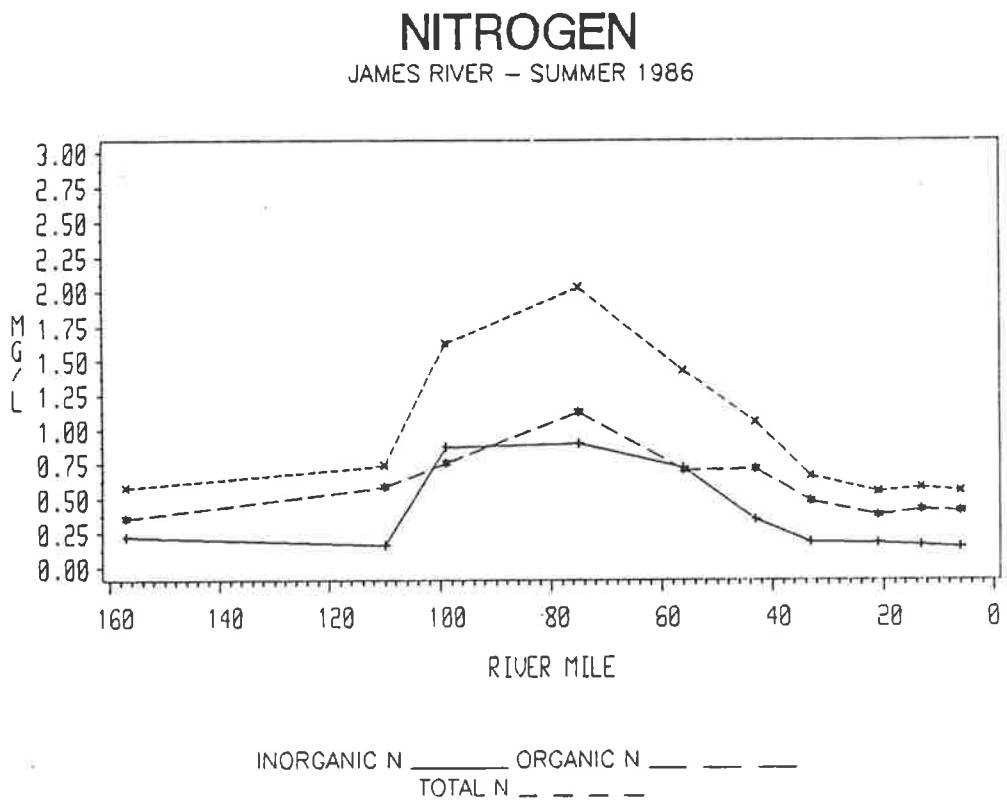


FIGURE 5.30B


NITROGEN
JAMES RIVER – SUMMER 1986
MG/L
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
160
140
120
100
80
60
40
20
0
RIVER MILE
INORGANIC N
ORGANIC N
TOTAL N

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PHOSPHORUS

Orthophosphate

Based on the EPA report, 18% of the orthophosphate loading to the James originates above the fall line (Table V). The concentrations at the fall line exhibited a general increase from February through October (Figure 5.31). During winter, the average fall line concentration was 0.14 mg/l. This decreased to 0.06 mg/l during spring and then increased as streamflow decreased, reaching an average concentration of 0.33 mg/l during fall. These high levels at the fall line decreased to more moderate levels between the fall line station and Richmond (Figure 5.32). Municipal discharges account for 82% of the orthophosphate input to the James and this impact is evident as the large peak in orthophosphate concentration between Richmond and Hopewell (mile 99). Down river from this peak, orthophosphate concentration again decreases due to a combination of sediment sorption processes, biological uptake, and dilution. In the estuary, concentrations were generally low except during the summer and fall when concentrations were slightly elevated.

Particulate Phosphorus

Particulate phosphorus concentrations at the fall line ranged from less than 0.01 to 0.08 mg/l (Figure 5.31), and were generally lower than observed during 1984-1985. Values peaked at mile 99 during summer and at mile 33 during winter, while other seasons had variable concentrations with no clear spatial patterns (Figure 5.33).

FIGURE 5.31

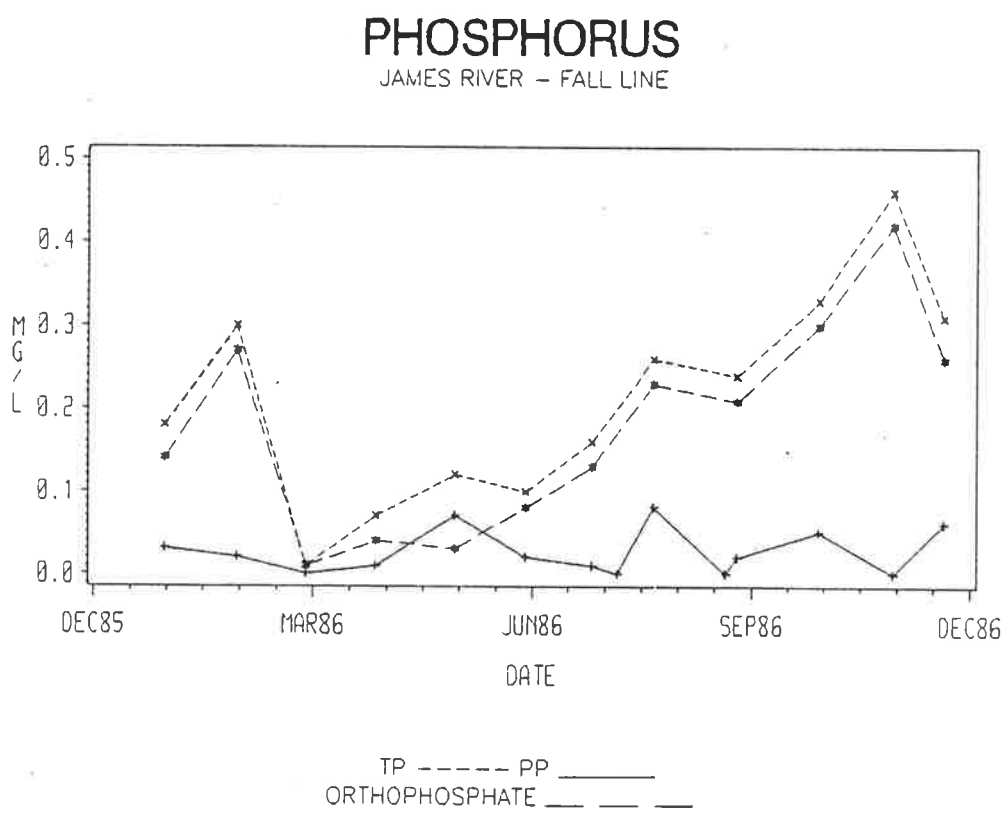


FIGURE 5.32

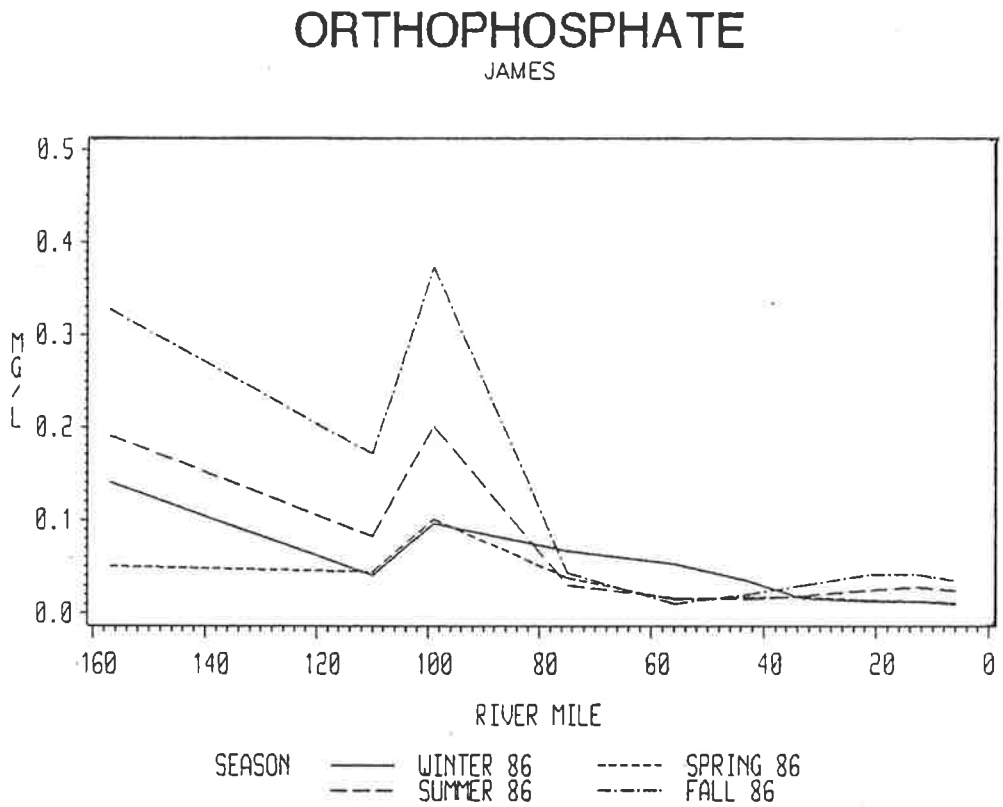
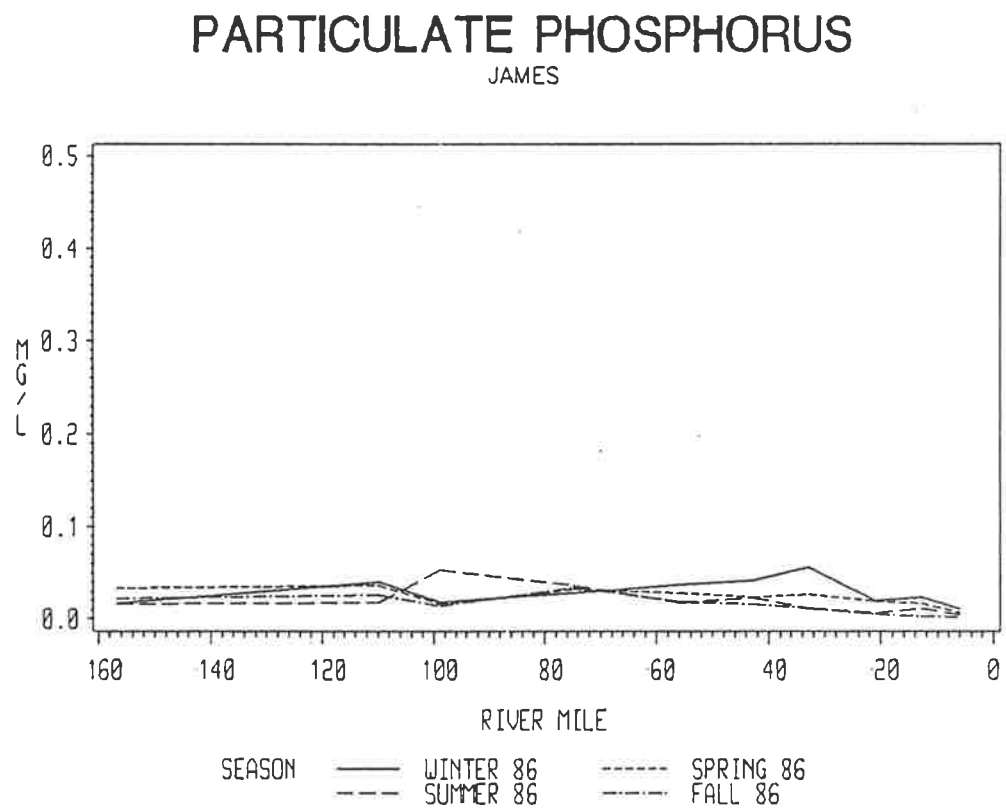


FIGURE 5.33



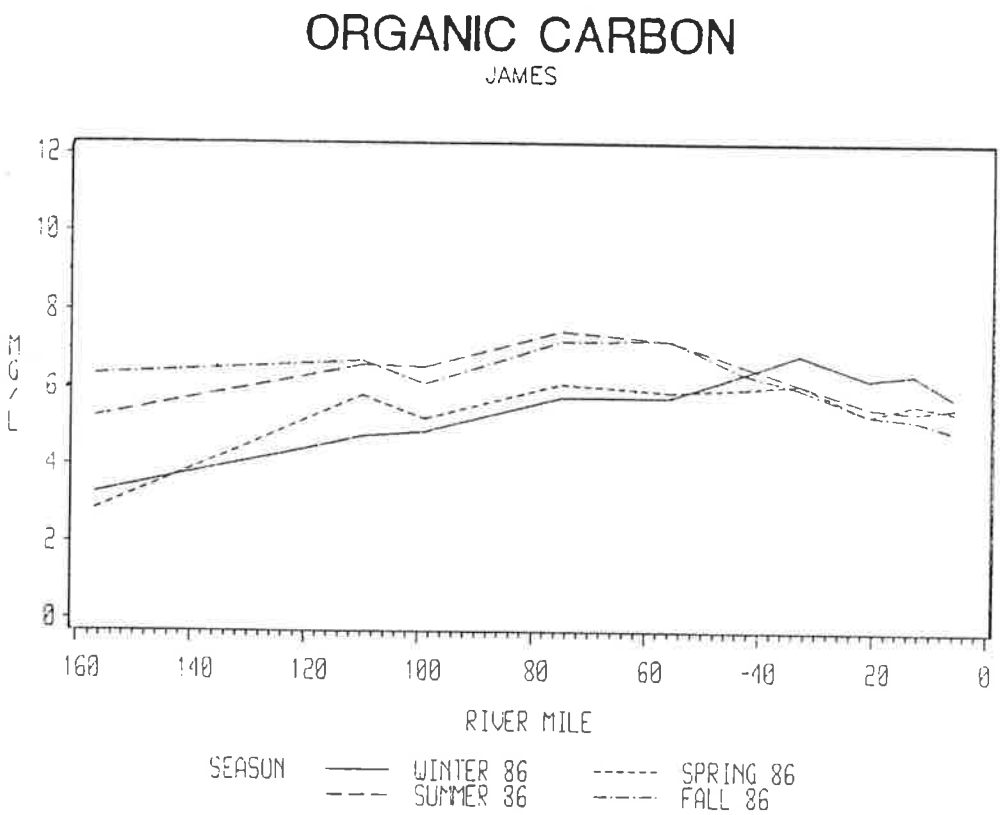
Total Phosphorus

Input across the fall line has been estimated as 27% of the total phosphorus in the James River (Table V). Concentrations at the fall line ranged from 0.02 to 0.48 mg/l and were dominated by orthophosphate on all but one date (Figure 5.31). An analysis of historical fall line data has shown that total phosphorus concentrations at the fall line of the James has almost doubled since 1974 and is increasing at a rate of about six percent a year (USGS, Report VA. 85-1, 1985). This increase, mostly orthophosphate, may mean that present estimates of the relative roles of nonpoint versus point source inputs are incorrect. The cause of the high fall line concentrations is not apparent, but it is an important factor which may affect the water quality of the James and deserves greater attention. The longitudinal distribution of total phosphorus was similar to that of orthophosphate.

ORGANIC CARBON

Organic carbon concentrations at the fall line of the James ranged from 1.8 to 7.0 mg/l. In the tidal freshwater and transition areas, organic carbon concentrations were higher in the summer and fall than in the winter and spring (Figure 5.34). The higher carbon concentrations during summer and fall may be a result of higher biological productivity during these months. Another contributing factor is probably the higher streamflow during winter and spring which may dilute the riverborn carbon and decrease the concentration during these seasons. In the estuary, below mile 40, the winter season had higher concentrations than the other seasons due to production by estuarine phytoplankton.

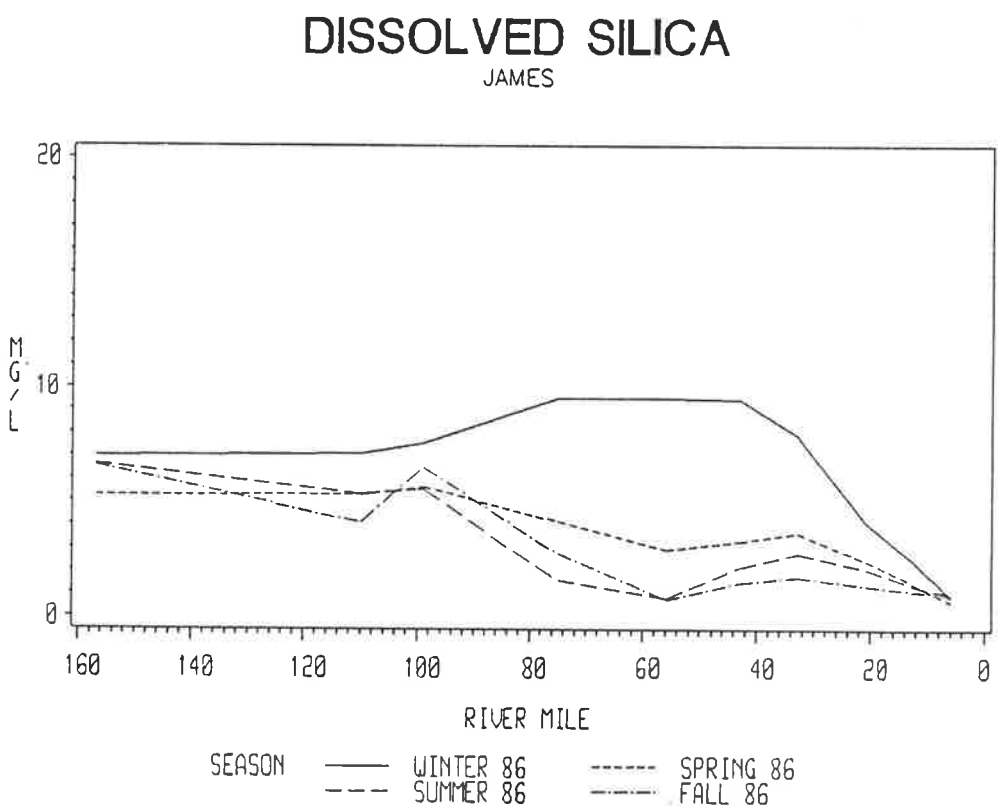
FIGURE 5.34



SILICA

Silica concentrations at the fall line ranged from 1.7 to 8.8 mg/l. The seasonally averaged distribution of silica throughout the river is presented in Figure 5.35. During winter, when biological uptake is lowest, silica remains high in the freshwater zone and decreases in the estuary due to dilution. During the other seasons a decrease was observed in tidal freshwater (miles 80-50) followed by a subsequent increase down river. The decrease in concentration results from uptake by freshwater diatoms whose production is highest in the area just before the freshwater and saltwater interface. The increasing concentration further down river is the result of remineralization of the silica that was previously taken up by diatoms. Progressing further down river, the concentration again decreases due to the uptake by estuarine diatoms as well as dilution by Bay water.

FIGURE 5.35



RIVER COMPARISONS

NITROGEN

In general, the comparisons between rivers revealed the same patterns as observed during the 1984-1985 monitoring period. As seen previously, several differences between rivers are evident which can be attributed to unique patterns of nutrient inputs. Figure 5.36A compares the inorganic nitrogen concentration of the three rivers during the high streamflows of winter. The Rappahannock, being dominated by nonpoint inputs above the fall line, exhibited high inorganic nitrogen concentrations from the fall line through tidal freshwater. In the York and James, inorganic nitrogen reached a maximum concentration in tidal freshwater, indicating a source of nitrogen below the fall line. In the James, the peak in inorganic nitrogen was due to point source inputs in the Richmond/Hopewell area. In the York River, the peak in inorganic nitrogen was probably the result of nonpoint input from the bordering wetlands or upland areas below the fall line. In the estuarine areas of the three rivers, inorganic nitrogen concentrations are low due to dilution by Bay water.

During the extremely low streamflows of fall 1986, point source discharges to the James had a much more pronounced influence than during the winter (Figure 5.36B). Conversely, the nonpoint inputs to the York and Rappahannock are decreased during a low flow period and this, as well as biological uptake, creates low concentrations in those rivers. During the warmer seasons, ammonia release from sediments in the estuary is stimulated by conditions of low dissolved oxygen in the York and Rappahannock but not the James.

Concentration and distribution of organic nitrogen was relatively similar among the three rivers. During winter, all three rivers had a peak in the estuarine area due to phytoplankton production (Figure 5.37A). In the fall, the peak concentrations were further up river (Figure 5.37B). For the James, this fall peak is related to both point source inputs and algal production. The Rappahannock peak is mainly a result of high algal production. The York has neither the high point source inputs of the James or the high algal production of the Rappahannock. However, it has extensive tidal wetlands which probably account for the majority of its organic nitrogen input.

FIGURE 5.36A
INORGANIC NITROGEN
ALL RIVERS – WINTER 1986

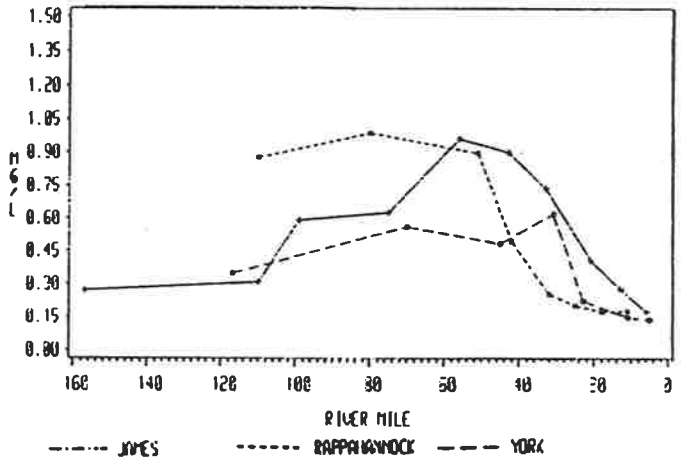


FIGURE 5.36B
INORGANIC NITROGEN
ALL RIVERS – FALL 1986

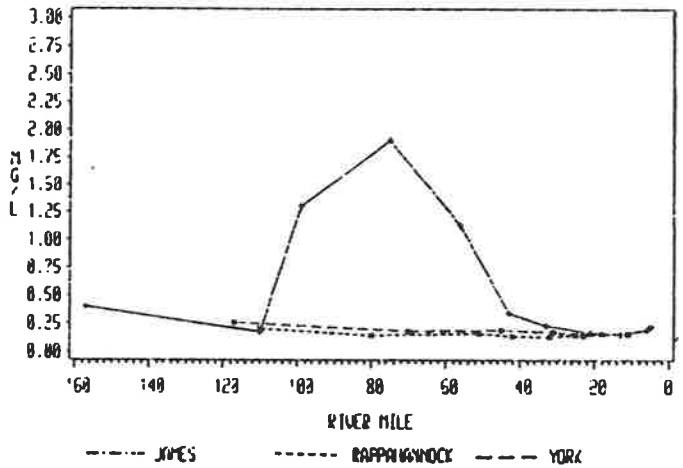


FIGURE 5.37A
ORGANIC NITROGEN
ALL RIVERS – WINTER 1986

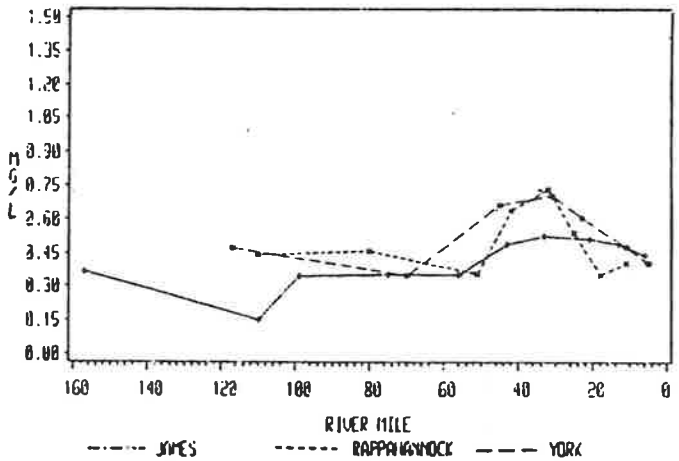
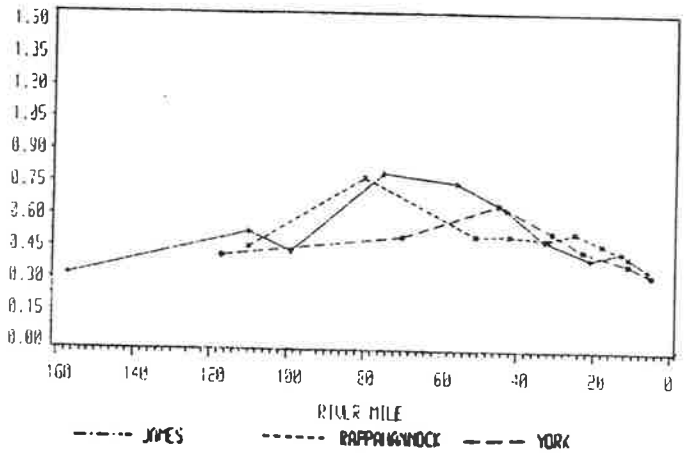


FIGURE 5.37B
ORGANIC NITROGEN
ALL RIVERS – FALL 1986



PHOSPHORUS

The fall line input of phosphorus was highest in the James due to high orthophosphate concentrations (Figure 5.38). As observed in previous reports, the James has much higher phosphorus concentrations at the fall line than the other rivers. The York had the next highest concentration at the fall line, unlike during 1984-1985 when the York and Rappahannock exhibited similar phosphorus concentrations. The reasons for these elevated phosphorus concentrations at the fall line of the James are presently not well understood.

A comparison of longitudinal profiles of orthophosphate in the three rivers during fall is given in figure 5.39. The large increase in the James that occurred between Richmond and Hopewell (mile 99) is due to loadings from Richmond area municipal dischargers. The combination of high fall line and point source loadings of orthophosphate results in generally higher orthophosphate concentrations throughout most of the James. Unfortunately, the possible impact of point sources input of phosphorus to the upper tidal Rappahannock is not detected by the current program.

All the rivers had elevated concentrations of orthophosphate in the estuary during some seasons, though to a different degree and for slightly different reasons. In the Rappahannock the elevated levels are a result of hydrologic conditions which lead to low dissolved oxygen concentrations in the bottom waters and subsequent release of orthophosphate from the

FIGURE 5.38

TOTAL PHOSPHORUS

FALL LINE

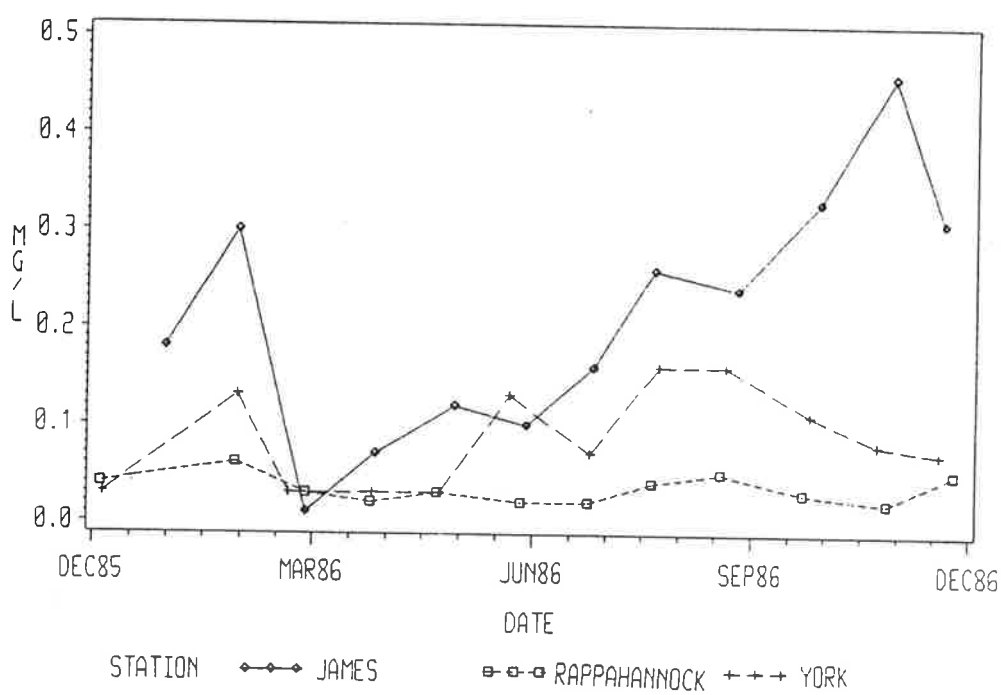
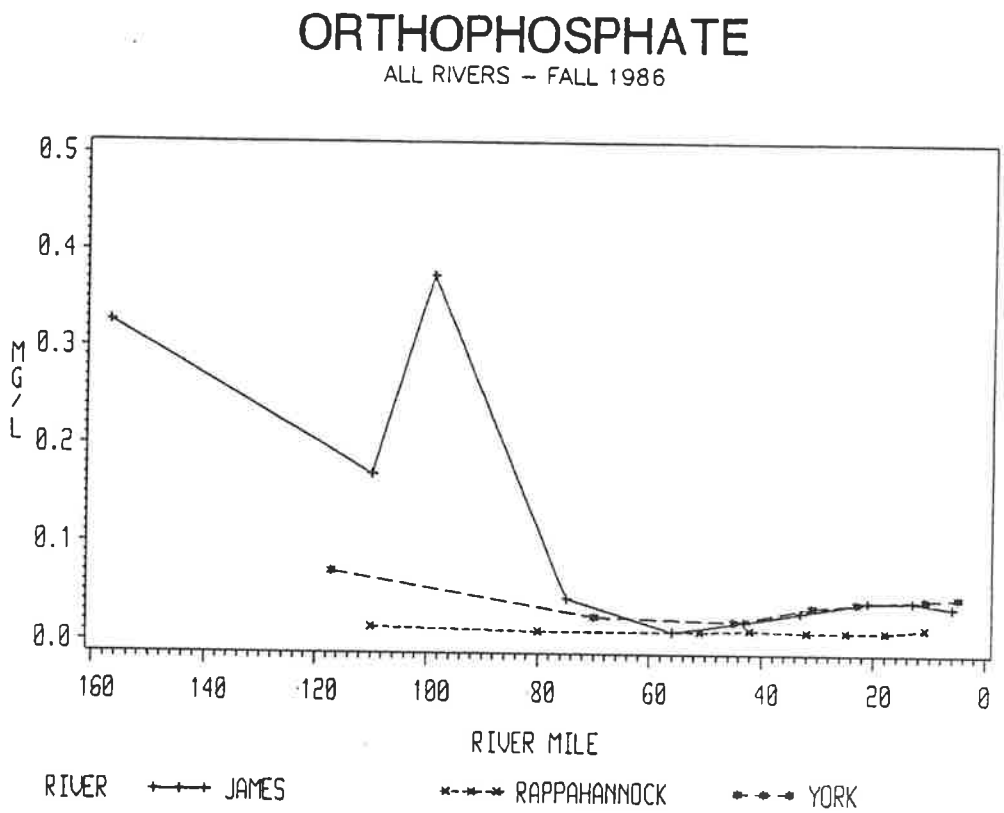


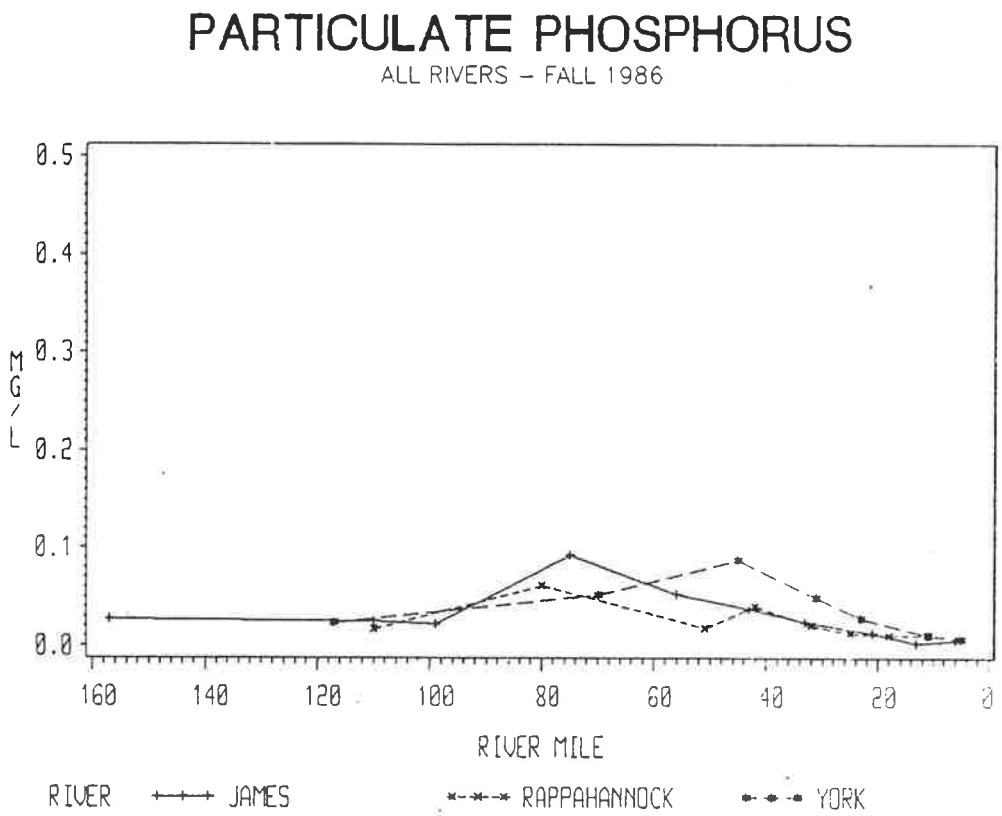
FIGURE 5.39



sediment. In the estuarine portion of the York, the same type of sediment release is active to a lesser extent and there is also a small but significant amount of point source input. The estuarine James does not experience phosphorus releases from the sediment driven by low oxygen, but has greater point source inputs which contribute phosphorus.

Particulate phosphorus generally exhibited a peak in concentration in the tidal freshwater and upper transition zones of the three rivers (Figure 5.40). In the James, the elevated concentrations at mile 75 were largely a result of algal production. The York had consistently elevated concentrations of particulate phosphorus at mile 45, largely resulting from detritus export from wetlands. The Rappahannock typically exhibited a broader peak in concentration of particulate phosphorus, extending from tidal freshwater into the oligohaline zone.

FIGURE 5.40



ORGANIC CARBON

Of the three tributaries, the York had the highest concentration of organic carbon at the fall line on all but one sampling date (Figure 5.41). Figure 5.42 compares the longitudinal distribution of organic carbon throughout the three rivers during winter. During this, as well as all other seasons, the York continued to exhibit the highest organic carbon concentration throughout most of the river, except in the estuary where organic carbon concentrations were similar among rivers. The higher concentrations of organic carbon in the York were particularly evident in the salinity transition zone. The James and Rappahannock exhibited an increase in organic carbon in the estuary particularly during winter and spring, possibility reflecting the spring diatom bloom. All rivers exhibited higher concentrations at their fall line and tidal freshwater stations during the summer and fall than in winter or spring. This probably resulted from both higher biological productivity as well as lower dilution during summer and fall.

FIGURE 5.41

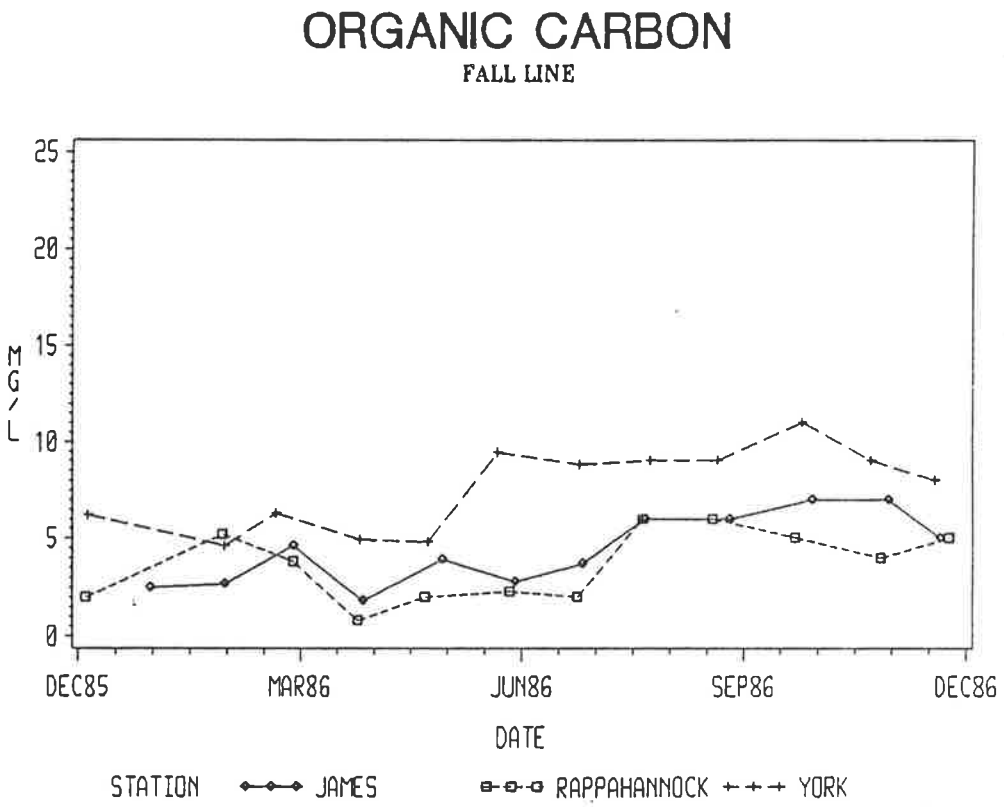
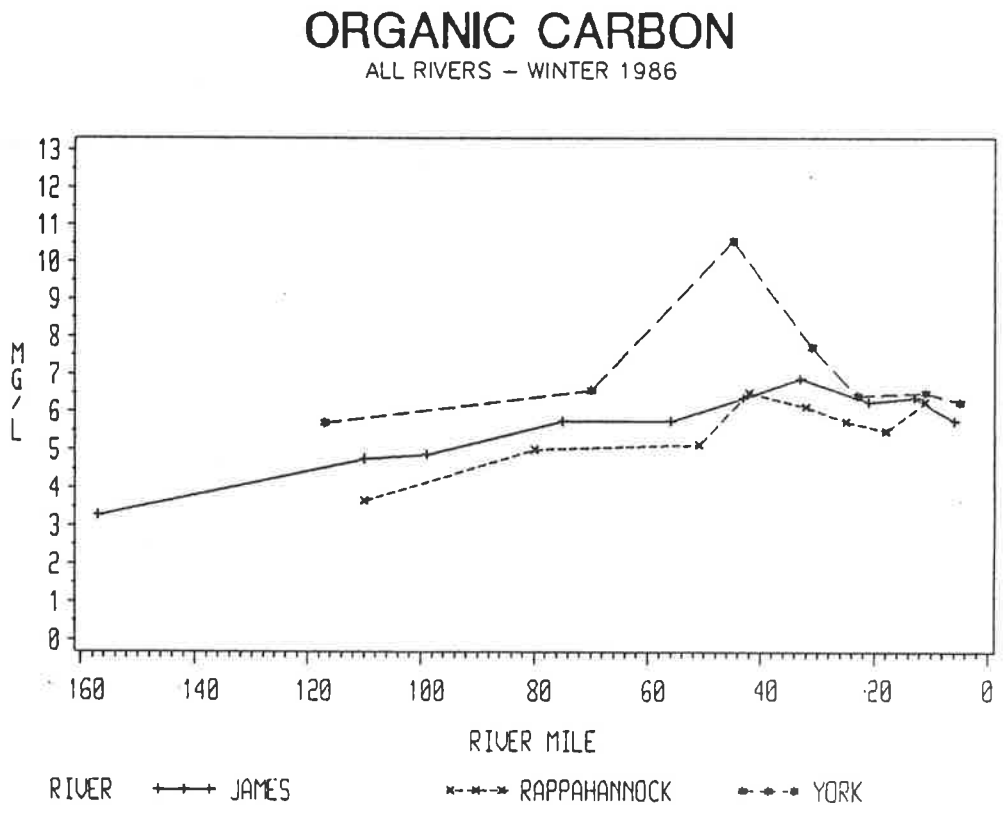


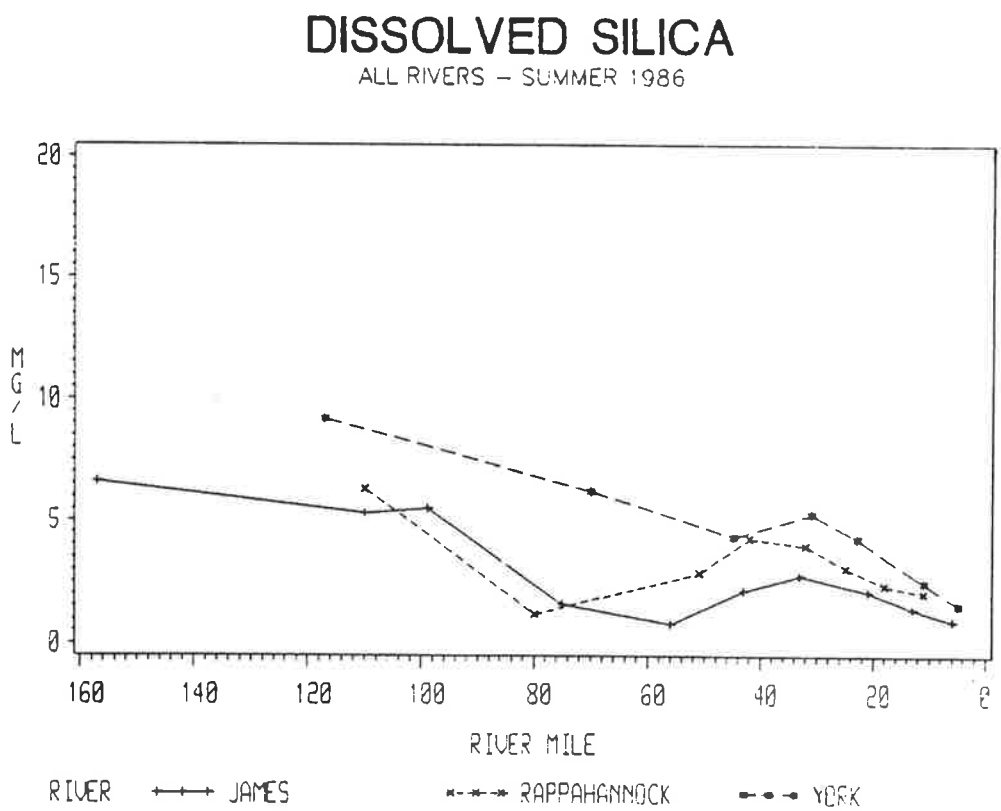
FIGURE 5.42



SILICA

The concentration of silica at the fall line of the three rivers did not appear to have a seasonal or streamflow related pattern. During the first half of 1986, the York and Rappahannock exhibited silica concentrations generally higher than in the James. During the second half of 1986, the York retained high concentrations while the James and Rappahannock exhibited lower concentrations. All three rivers exhibited a strong pattern of biological cycling of silica during the year (Figure 5.43). In the tidal freshwater portions of the tributaries, silica concentrations decreased due to uptake by freshwater diatoms. Down river, near the limit of salinity intrusion, silica concentrations increased due to remineralization of particulate silica. In the estuary, silica concentrations decreased again as a result of uptake by estuarine diatoms and dilution by Bay waters. This pattern was evident during all seasons except winter. The tidal Pamunkey and York generally exhibited the highest silica concentrations of the three tributaries, this is probably related to the lower algal production of the York.

FIGURE 5.43



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VI. RESPONSE VARIABLES

The previous chapters characterized water quality in terms of their physical and chemical variables. The physical variables are controlled primarily by the natural environment, while the chemical variables (nutrients) are the result of both natural and anthropogenic inputs and instream cycling. This section will focus on measurements such as nitrogen/phosphorus ratios, chlorophyll-a, water clarity and dissolved oxygen. These variables respond to, or are a product of ,the physical and chemical variables previously discussed. These 'response variables' also interact with each other through a complex variety of chemical and biological relationships. The 'response variables' are often intended to be indirect indicators or measurements of other variables; e.g. chlorophyll-a concentration is a measurement of algal biomass. The 'response variables' are usually more readily associated with water quality problems than the physical or chemical variables. Conditions such as low dissolved oxygen, high chlorophyll levels, and high turbidity directly impact the quality of a water body, but defining the cause of the problem is a complex task.

NITROGEN/PHOSPHORUS RATIOS

Most of the data presented in the previous chapter focused on actual instream concentrations of different chemical forms of nitrogen and phosphorus. In addition to the actual concentrations, the relative abundance of nitrogen (N) to phosphorus (P) is an important characteristic of each tributary. Phytoplankton production is controlled by the availability of nutrients such as nitrogen and phosphorus, as well as other factors such as predation, temperature, and sunlight. A typical phytoplankton community requires approximately 16 atoms of nitrogen for every atom of phosphorus utilized for growth. When the ratio of nitrogen to phosphorus exceeds 16:1, then phosphorus is in short supply relative to nitrogen, thus becoming the nutrient limiting growth. When the ratio is below 16, then nitrogen becomes the limiting nutrient. Freshwater is typically phosphorus limited due to high concentrations of nitrate, while marine water is nitrogen limited because of its very low nitrogen concentration. The estuary, which is a gradient between fresh and marine water, exhibits both phosphorus and nitrogen limitation varying by location and season.

N/P ratios describe which nutrient may be limiting phytoplankton production. In areas where high algal production is creating a water quality problem, managers can implement strategies to control the limiting nutrient(s) and reduce phytoplankton production. These ratios may also be beneficial when considering a nutrient management strategy for an area which receives a heavy nutrient loading from upstream. Though a freshwater river high in nitrogen may not experience algal blooms due to phosphorus limitation, a nitrogen limited estuary located downstream from this river may experience blooms due to the high nitrogen loadings from upstream.

The results of the laboratory analyses, which are recorded in mg/l as N or P, must be converted to ug atoms/liter prior to calculating N/P ratios. There are two different types of N/P ratios that can be calculated. The ratio of dissolved inorganic nitrogen (NO23 + NH4) to

dissolved inorganic phosphorus (orthophosphate) can be calculated. A DIN/DIP ratio measures only the dissolved nutrients in the water column which are immediately available for phytoplankton uptake. This calculation may be appropriate if algal production is low, but during periods of high production much of the nitrogen and phosphorus is incorporated into organic compounds within the algal cells. These compounds can be quickly recycled within the algae population. So, DIN/DIP ratios do not adequately account for organic nitrogen and phosphorus which may represent the majority of nutrients available to algal populations. Another problem with calculating DIN/DIP ratios is that a large number of observations are below the detection limits for orthophosphate, nitrite, and ammonium (Table VII). This results in a ratio of detection limits and not true concentrations, which cannot be used for data analysis.

The second ratio that can be calculated is total nitrogen/total phosphorus (TN/TP). This ratio measures the dissolved and particulate fractions of nitrogen and phosphorus, thus presenting a more accurate representation of the nutrient ratios. With this ratio, both the dissolved nutrients available for algal uptake and those already incorporated into algal cells can be taken into account. The data from which TN/TP ratios are calculated are not as likely as DIN\DIP ratios to be below detection limits, thus providing more data for an analysis. For these reasons, TN/TP ratios were used in this report. Seasonally averaged TN/TP ratios were calculated for each station. Since the ratio of 16:1 is an approximate value which changes with phytoplankton species composition, in this report TN/TP ratios were classified as nitrogen limited (< 10), phosphorus limited (>20) or intermediate (10 - 20). The percentage of ratios in each one of these categories was determined for each station.

CHLOROPHYLL-A

Chlorophyll-a is a pigment found in plants, including phytoplankton, which is necessary for photosynthesis. Since this compound is unique to plants, analyses for chlorophyll-a can provide an indirect measurement of algal concentration or biomass in the water column. As primary producers in aquatic systems, phytoplankton are the base of the food web which supports the biological community. Low to moderate chlorophyll-a concentrations indicate a normal algal abundance while high chlorophyll-a concentrations often indicate a system that is experiencing high loadings of nitrogen and/or phosphorus, a condition termed 'nutrient enriched'. These high algal concentrations can create many water quality problems. During daylight, algae photosynthesize and produce oxygen, while at night algae respire and consume oxygen from the water column. This creates a diurnal or daily swing in dissolved oxygen, resulting in supersaturation in the day and hypoxic conditions during the night. When large algal populations die off and settle out of the water column, the decay of this organic matter also consumes large amounts of oxygen.

Phytoplankton, or 'algal', blooms are natural phenomena but species composition, duration, and intensity can be altered by anthropogenic impacts. Different types of phytoplankton reach maximum population levels or 'bloom' at various times of the year. Diatoms, which are the major algal group grazed by zooplankton and fishes, typically bloom in the estuary in the late winter and early spring. They also can produce a less

TABLES VII

PERCENT OF ANALYTICAL RESULTS BELOW DETECTION LIMIT

RIVER SECTION

	Fall Line	Tidal Fresh (TF)	Transition (RET)	Estuary (LE)
Rappahannock				
NH34	27	29	71	69
NO3	36	27	38	50
NO2	45	82	91	76
TKN	0	0	0	0
PO4	54	30	58	57
TP	0	0	1	<1
York				
NH34	10	28	50	58
NO3	5	8	8	51
NO2	25	95	68	67
TKN	0	0	0	0
PO4	25	28	24	56
TP	0	0	0	0
James				
NH34	9	17	33	45
NO3	27	9	14	22
NO2	54	39	72	61
TKN	0	0	0	0
PO4	9	9	26	27
TP	0	0	0	0

intense fall bloom. The intensity and duration of the spring bloom and its contribution to oxygen consuming processes may be important in the establishment and continuation of low dissolved oxygen during the summer in the Chesapeake Bay and some of its tributaries. During the warmer summer months other groups of phytoplankton can reach bloom conditions. Very high populations of blue-green algae in freshwater can create aesthetic and drinking water problems. In estuarine waters, summer blooms of dinoflagellates are often termed 'red tides' and may produce toxins which can result in fish kills. High algal concentrations also reduce water clarity, preventing light from reaching submerged aquatic vegetation.

Within the Virginia CBP Tributary Water Quality Monitoring Program, chlorophyll-a collection started in the summer of 1985 and continues to the present. The chlorophyll-a data presented in this report has been corrected for pheophytin content, a breakdown product of chlorophyll-a.

WATER CLARITY

Water clarity is an important characteristic of any aquatic system. The depth to which light penetrates a water column determines the area where photosynthesis can take place. Submerged aquatic vegetation (SAV) can only exist where light penetration reaches the sediments. The reduction of water clarity has been cited as a contributing factor in the decline of SAV in the Chesapeake Bay. Phytoplankton can also be limited by water clarity. In areas of high non-point source runoff, high loads of suspended sediment can reduce light penetration and limit phytoplankton production. In areas of high algal production, the algal biomass near the surface can also reduce light penetration, thus limiting algal production in deeper water as well as SAV production near the bottom.

Secchi depth is a direct measurement of water clarity and an indirect measurement of of light penetration. Greater secchi readings indicate increased water clarity and lower secchi readings indicate less water clarity. Water clarity is a function of the concentration of suspended sediment and organic matter in the water column, thus secchi depth acts as an indirect measurement for these parameters. Suspended sediments are characteristic of agricultural and urban runoff. Sediment is also resuspended from the river bed into the water column. Extremely high concentrations, as seen during major storm events, impact living organisms by burial, and by interfering with respiration and reproduction. The suspended sediments may also carry a large load of phosphorus adsorbed to the surface of clay particles. Organic matter in the water collumn can be in the form of living or dead phytoplankton and bacteria. It can also be detritus (dead organic matter) transported into the river from wetlands and terrestrial habitats.

DISSOLVED OXYGEN

Dissolved oxygen is a important indicator of water quality. Low oxygen (hypoxia), or no oxygen (anoxia), has been identified as one of the major problems facing the Chesapeake Bay and some of its tributaries. A lack of adequate oxygen in a habitat precludes its use by most aquatic organisms; thus many benthic organisms which would normally serve as food for predatory fish are absent in areas impacted by hypoxia. Periodic

upwelling of hypoxic water into near shore areas causes mortality in shellfish beds. Anoxic water also contributes to the problems of nutrient enrichment. In the absence of oxygen, both nitrogen and phosphorus compounds can flux out of the sediment into the overlying water column.

The dissolved oxygen content of a water body changes in response to many physical and biological processes. Both temperature, and to a lesser extent salinity, control the amount of oxygen that can be dissolved in the water column (i.e. saturation level). Oxygen demands from processes in the sediment and water column, and oxygen production from photosynthesis modify the actual dissolved oxygen concentrations. The atmosphere, a large source of oxygen for the surface waters, introduces oxygen through diffusion and turbulent mixing. Photosynthesis also introduces dissolved oxygen into the surface water, even to the point of supersaturation during intensive algal blooms. The water near the bottom of the water column receives oxygen from the surface through vertical mixing. Throughout much of the year, when temperatures are low and the water column is well mixed, oxygen concentrations are near saturation. During the late spring and summer, rising water temperatures and increasing water column and sediment oxygen demands, coupled with limited vertical mixing, combine to cause the depletion of oxygen in the deeper waters.

Virginia has a dissolved oxygen water quality standard for estuarine waters of 4.0 mg/l, below which is generally considered hypoxic conditions. The number of violations of the standard as measured in this program is a conservative estimate. Sampling occurs during daylight when dissolved oxygen concentrations are near their maximum. If sampling was conducted just prior to daylight, when dissolved oxygen is at the minimum of the diurnal swing, then a larger percentage of violations of the standard would be expected.

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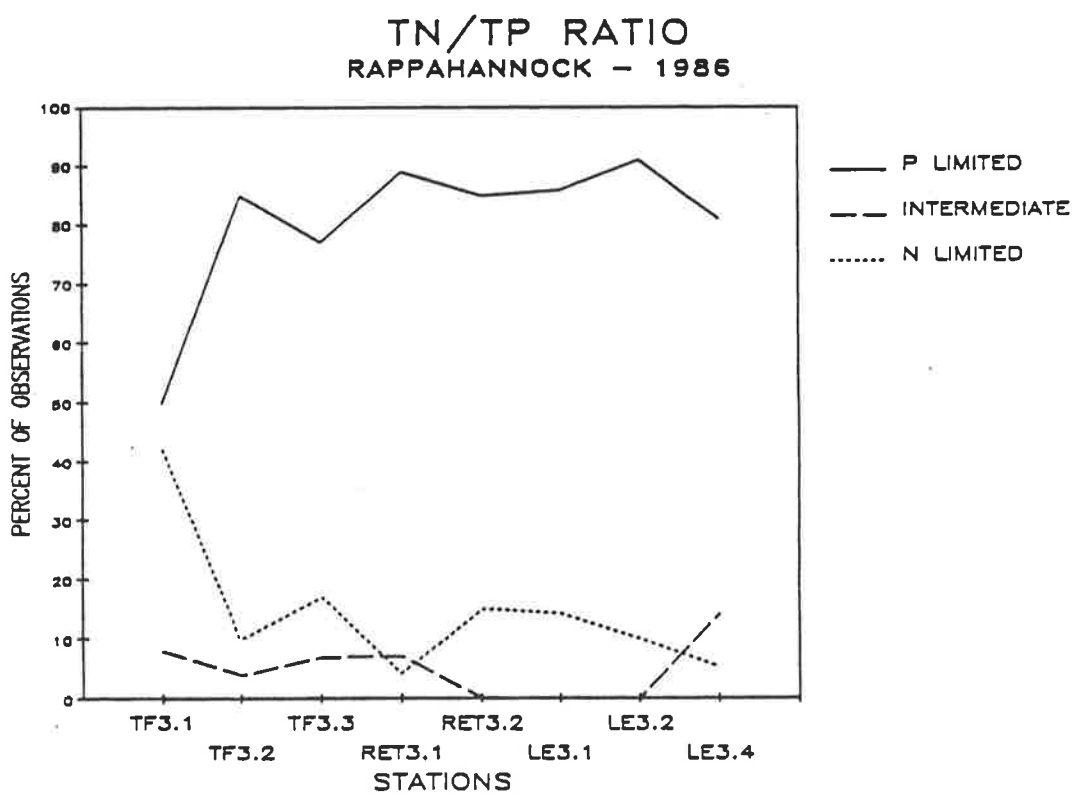
RAPPAHANNOCK RIVER

N/P RATIOS

The number of nutrient concentrations below the limit of detection were quite high, resulting in few TN/TP ratios being calculated. Most stations had 20 to 30 calculated ratios, but few in the summer due to the low concentrations of nutrients during this season. General patterns for the river can be described, but detailed comparisons between seasons are limited. Generally, over 75% of the TN/TP ratios in the Rappahannock indicated phosphorus limitation, while 5 to 15% indicated nitrogen limitation (Figure 6.1). At the fall line, TN/TP ratios were about equally divided between phosphorous and nitrogen limitation. The low phosphorus concentrations in the Rappahannock resulted in the predominance of phosphorus limitation during the majority of the year. During the summer when nitrogen concentrations are also low, TN/TP ratios may be lower. Even though the Rappahannock was generally phosphorus limited during 1985, the river was even more predominately phosphorus limited during 1986.

FIGURE 6.1



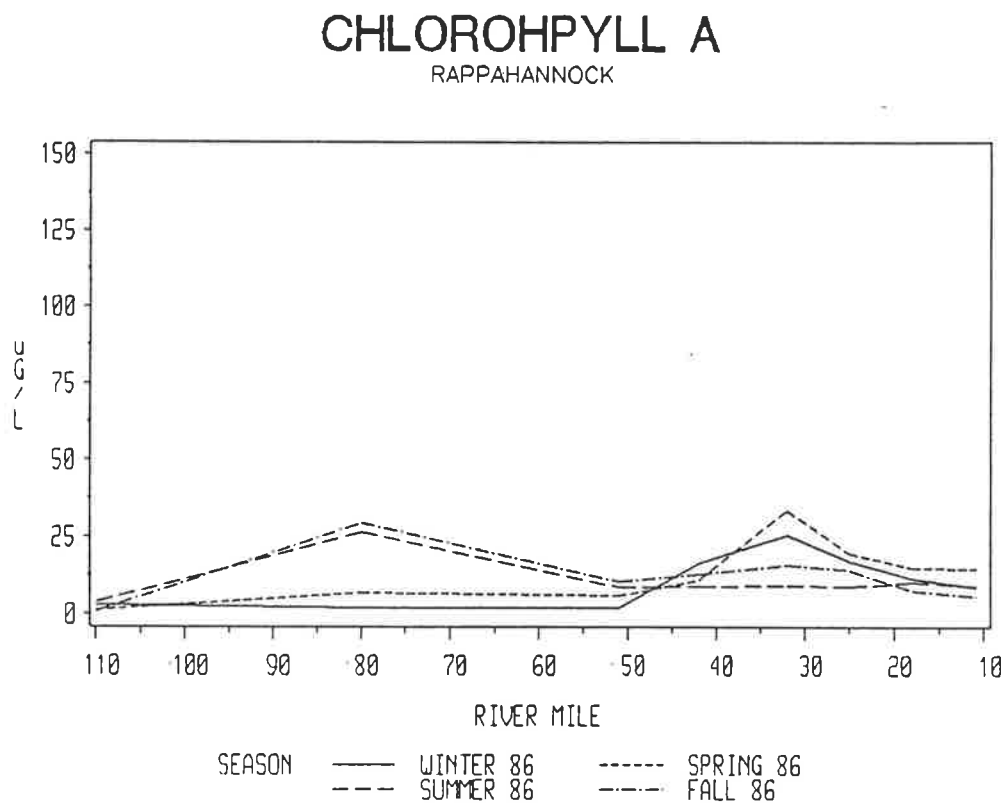
CHLOROPHYLL-A

The concentration of chlorophyll-a at the fall line of the Rappahannock, as was the case with all the tributaries, was very low. Most algae above the fall line is benthic (i.e. periphyton), while in the tidal portion of the river the majority of algae is planktonic or free floating. There are no stations located in the first 25 miles below Fredericksburg. As a result, there is poor monitoring coverage of the tidal freshwater section of the river. In the previous report chlorophyll-a data was only available for the summer and fall, but for this reporting period a full year of data was available.

Although chlorophyll-a concentrations during the winter and spring were very low in the upper tidal Rappahannock, a major peak in chlorophyll-a was evident in the lower estuarine Rappahannock (Figure 6.2). Chlorophyll-a concentrations peaked at mile 32 (RET3.2) which exhibited salinities averaging 10 ppt. Average chlorophyll-a concentrations during the winter and spring ranged from 25 to 35 ug/l with a maximum of 60 to 80 ug/l. The estuarine peak in chlorophyll-a reflects the typical late winter and spring bloom of estuarine phytoplankton, particularly diatoms.

As the winter/spring estuarine bloom declined, the summer tidal freshwater bloom become evident. Station TF3.2, the only tidal freshwater station sampled by this program, exhibited an average chlorophyll-a concentration of 26 ug/l, with a maximum of 43 ug/l. Chlorophyll-a concentrations may be greater upriver between station TF3.2 and

FIGURE 6.2

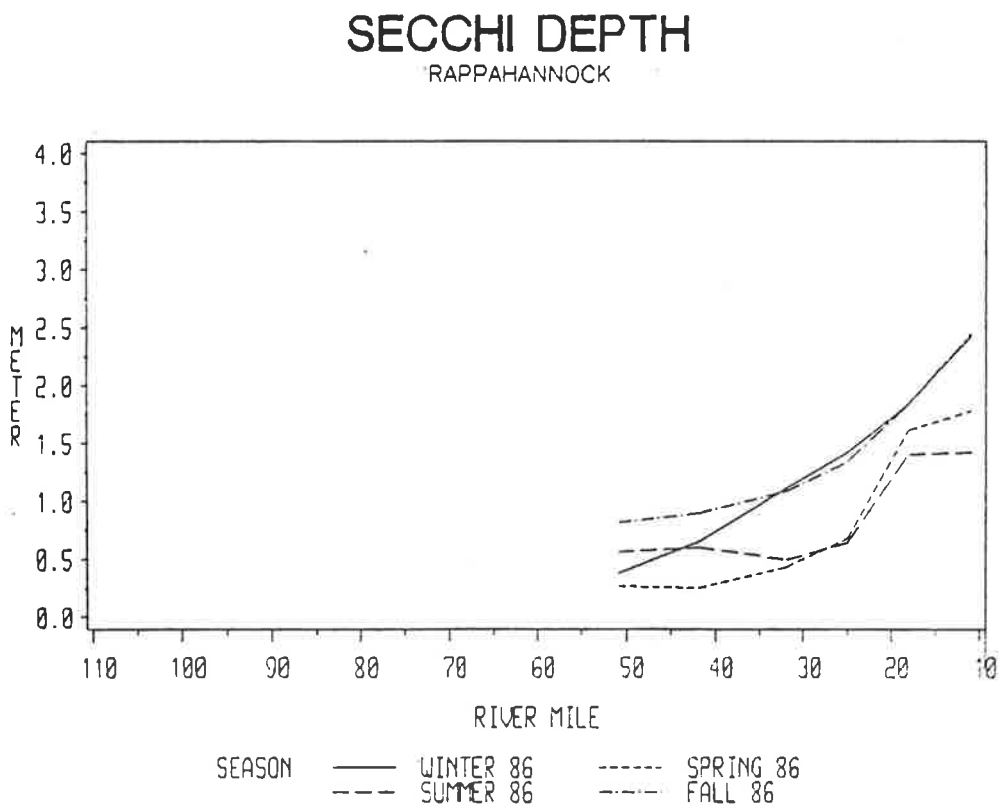


Fredericksburg. During the summer, the estuarine stations exhibited very low concentrations (8 - 10 ug/l), except for short-term blooms of up to 18 ug/l. During the fall two peaks in chlorophyll-a were apparent. The tidal freshwater summer bloom extended through the fall, with concentrations similar to the summer. A less evident estuarine bloom occurred in late fall. The fall bloom of estuarine phytoplankton is a common occurrence but is usually less intense and of shorter duration than the winter/spring bloom.

WATER CLARITY

The amount of information on water clarity in the tidal freshwater section of the Rappahannock is limited because the only station in this area is located on a bridge which is not suitable for collecting secchi readings. During the winter, water clarity in the upper tidal Rappahannock was low (0.4 meters), but steadily increased downstream to a maximum of 2.4 m at the mouth of the river (Figure 6.3). Water clarity in the spring was also low in the upper tidal Rappahannock, reflecting the winter/spring increase in streamflow and associated input of suspended sediment. Unlike the winter, the water clarity in the spring remained low down river to mile 20, where a sharp increase in secchi readings occurred. The water clarity during the summer exhibited a pattern similar to the spring, but with slightly higher water clarity in the upper Rappahannock and slightly lower clarity toward the mouth. The fall exhibited much greater water clarity in the upper Rappahannock and a steady down river increase in secchi readings, with a maximum at the mouth of the river similar to the winter.

FIGURE 6.3



Two general spatial patterns are evident in water clarity. As seen in the winter and fall, water clarity steadily increases from tidal freshwater toward the mouth of the river, which can be attributed to normal dilution of turbid river water with less turbid bay water. The second pattern, which was also seen in 1985, is a fairly stable water clarity from tidal freshwater down river to mile 20, where a sharp increase in water clarity occurs. Downstream of this increase, average water clarity ranged from 1.4 to 1.8 m in the spring and summer to 2.4 m in the winter and fall. The reduced water clarity at the mouth of the Rappahannock during the spring coincides with the decrease in salinity in the central Bay, as discussed in chapter IV.

DISSOLVED OXYGEN

The Rappahannock has historically exhibited low dissolved oxygen (hypoxia) in the deep channel near the mouth of the river. One measure of the extent and duration of hypoxia is the number of observations recorded below the state's dissolved oxygen standard of 4.0 mg/l. In the Rappahannock the freshwater and transitional stations generally do not experience hypoxia, while the estuarine stations exhibit varying degrees of hypoxia depending on numerous hydrological and climatic factors. On an annual basis, 3 - 15% of the observations at the estuarine stations were below the standard (Figure 6.4). The majority of violations typically occur during the summer, with 8 - 48% of the observations at the estuarine stations below the standard during the summer of 1986 (Figure 6.4). The estuarine stations exhibited average summer dissolved oxygen concentrations ranging from 4.1 to 5.0 mg/l. The minimum concentration of 0.1 mg/l was recorded during August 1986 at stations LE3.2 and LE3.4.

The dissolved oxygen concentration of samples collected 1 meter above the sediment exhibit an inverse relationship with water temperature, resulting in the seasonal changes in dissolved oxygen. The normal seasonal fluctuation, as seen at station TF3.2 in Figure 6.5, usually does not result in hypoxic conditions, but the estuarine stations exhibited a much more dramatic decline in dissolved oxygen during the summer. This decline typically begins when water temperatures rise above 20°C, generally in June. By early to mid September the lower Rappahannock usually becomes well mixed and hypoxia is dissipated. During 1986, dissolved oxygen had started to decline by June, and reached a minimum in August, then rebound sharply in early September. A short term decrease in dissolved oxygen was recorded during early October. Similar short-term declines in dissolved oxygen were also seen in previous years in the tributaries and the Bay. It may be a response to the short-term bloom of estuarine phytoplankton that typically occurs in the fall.

Compared to the previously reported summers of 1984 and 1985, the summer of 1986 exhibited fewer violations of the dissolved oxygen standard, but still exhibited dissolved oxygen below 1.0 mg/l. The summer of 1984 experienced very low dissolved oxygen and a high percentage of violations of the standard. Hypoxia during the summer of 1985 was less prolonged and not as severe.

FIGURE 6.4

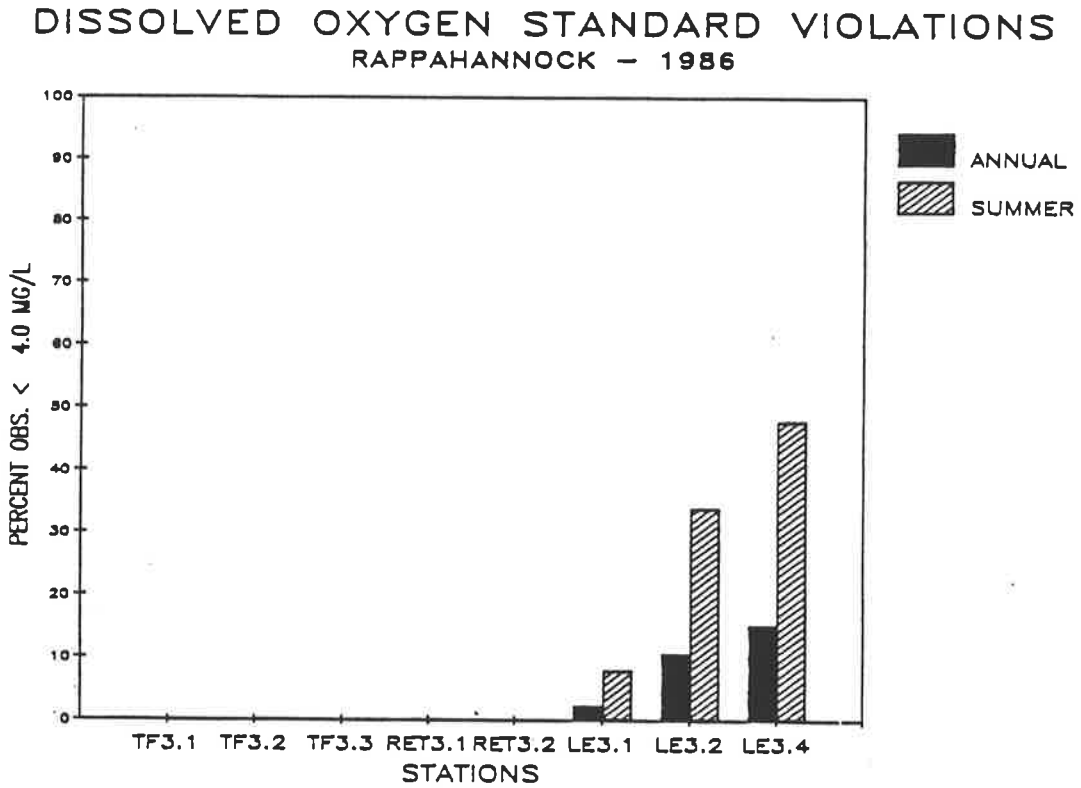
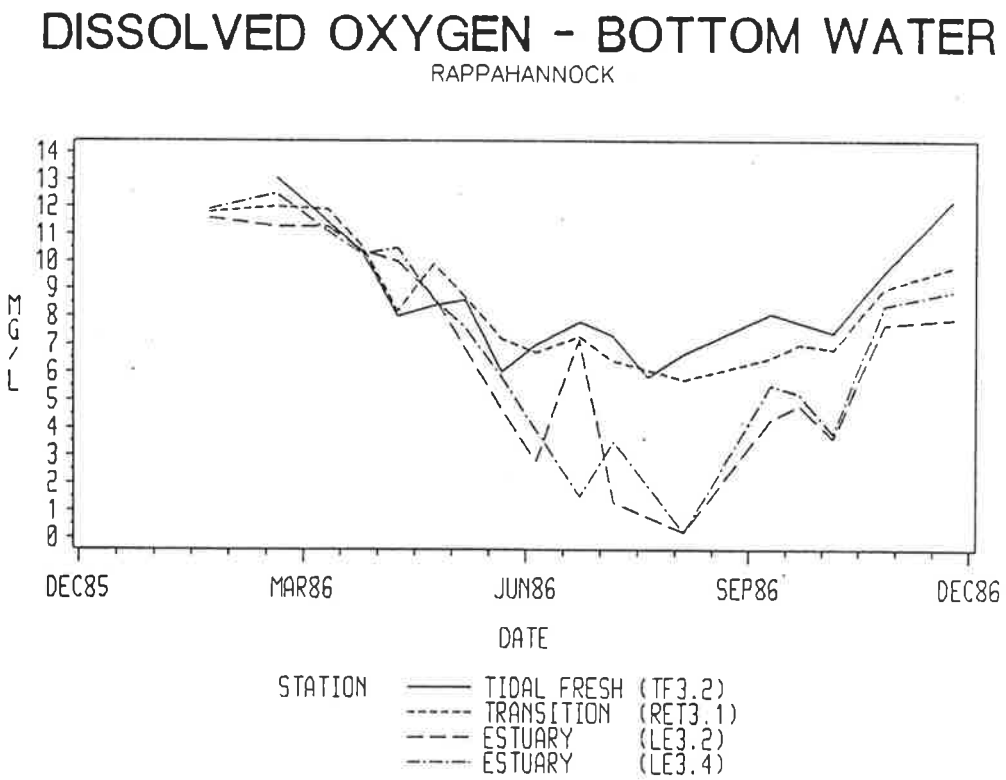


FIGURE 6.5



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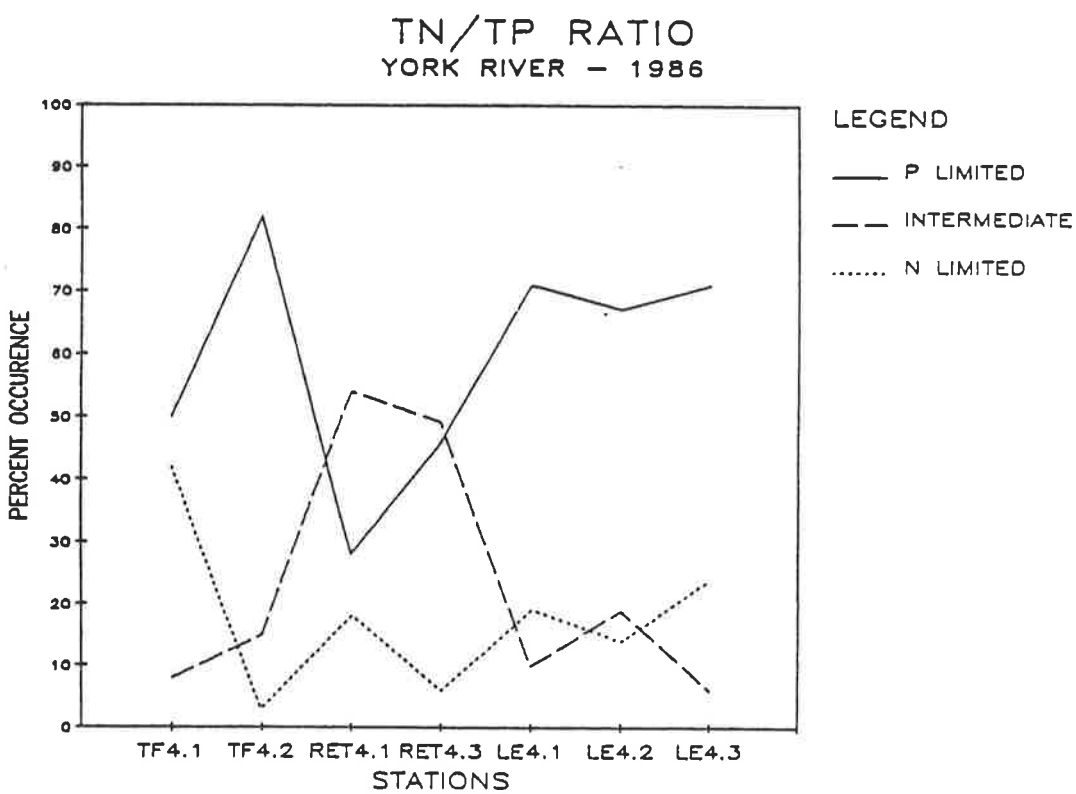
YORK RIVER

N/P RATIOS

A slightly larger number of TN/TP ratios (20-40) were calculated for each station in the York than in the Rappahannock. At the fall line of the Pamunkey, the occurrence of phosphorus and nitrogen limitation was approximately equal (Figure 6.6). In tidal freshwater of the Pamunkey, over 80% of the TN/TP ratios indicated phosphorus limitation but in the oligohaline zone (RET4.1) there was a marked increase in phosphorus concentrations, which resulted in lower TN/TP ratios indicating less phosphorus limitation. This decrease in TN/TP ratios was also apparent in 1985. At the estuarine stations, over 60% of the ratios indicated phosphorus limitation.

Examined on a seasonal basis, all stations exhibited over 70% phosphorus limitation in the winter, but this percentage decreased through the spring and summer into the fall. For example, station RET4.1 exhibited 75% phosphorus limitation in the winter, but this decreased to no phosphorus limitation by the fall. This may be a reflection of the decrease in streamflow and increase in salinity during the course of 1986.

FIGURE 6.6



CHLOROPHYLL-A

The York river exhibits a stable distribution of chlorophyll-a (Figure 6.7). This river appears to lack an intense summer phytoplankton bloom in tidal freshwater. The absence of this bloom makes estuarine phytoplankton the dominate factor influencing chlorophyll-a concentrations. A peak in chlorophyll-a is evident near the mouth of the river in the winter, which averaged 20 ug/l with a maximum of 34 ug/l. As the year progressed, this peak appeared to move slowly up river and at the same time decreased in intensity. During the summer and fall chlorophyll-a concentrations were low throughout the river with a small peak (< 10 ug/l) between miles 35 and 45.

WATER CLARITY

In the Pamunkey and York, the same general pattern in water clarity is apparent in all seasons. Water clarity decreases to a minimum at mile 45, then increased toward the river mouth. The tidal freshwater station (TF4.2) exhibits water clarity between 0.5 and 1.2 meters. The stations where water clarity is usually at a minimum (RET4.1), exhibited seasonal averages between 0.2 and 0.4 meters. The location of this station in the 'turbidity maximum' zone and flushing of the extensive marshes in the area are probably responsible for the low water clarity. A sharp increase in water clarity is evident between mile 10 and the mouth of the river, but not as pronounced as in the Rappahannock. The winter exhibited lower water clarity in tidal freshwater, then gradually increased down river to the mouth. Water clarity in the spring was higher in the tidal freshwater

FIGURE 6.7

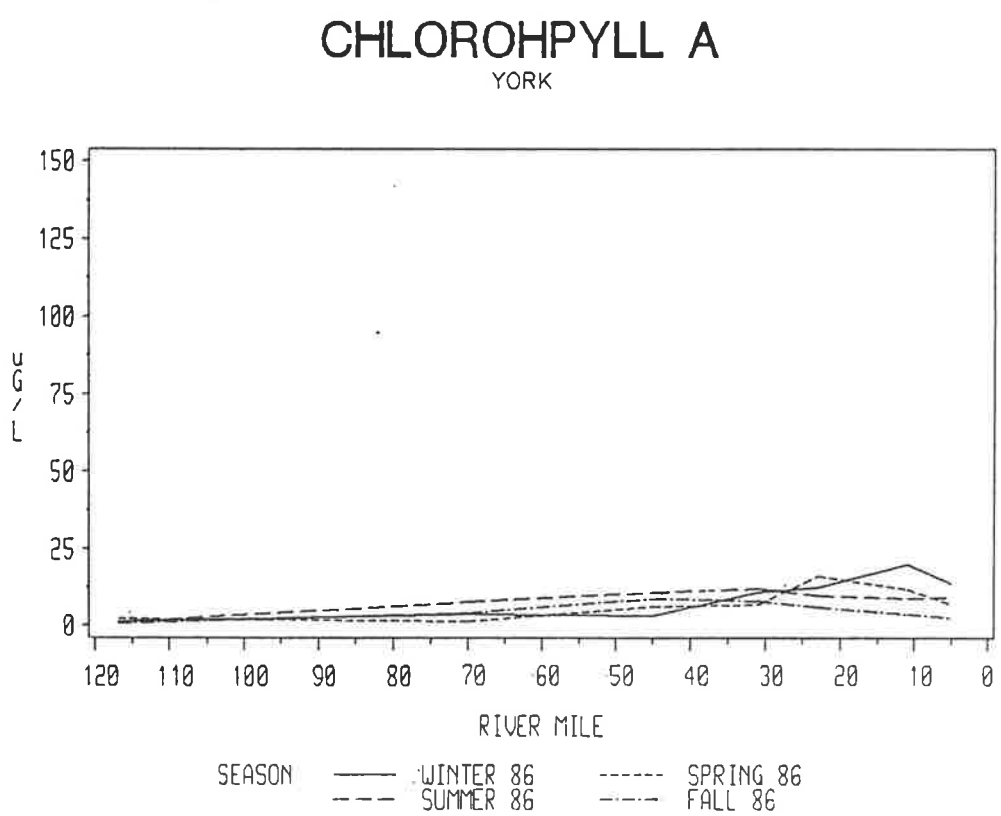
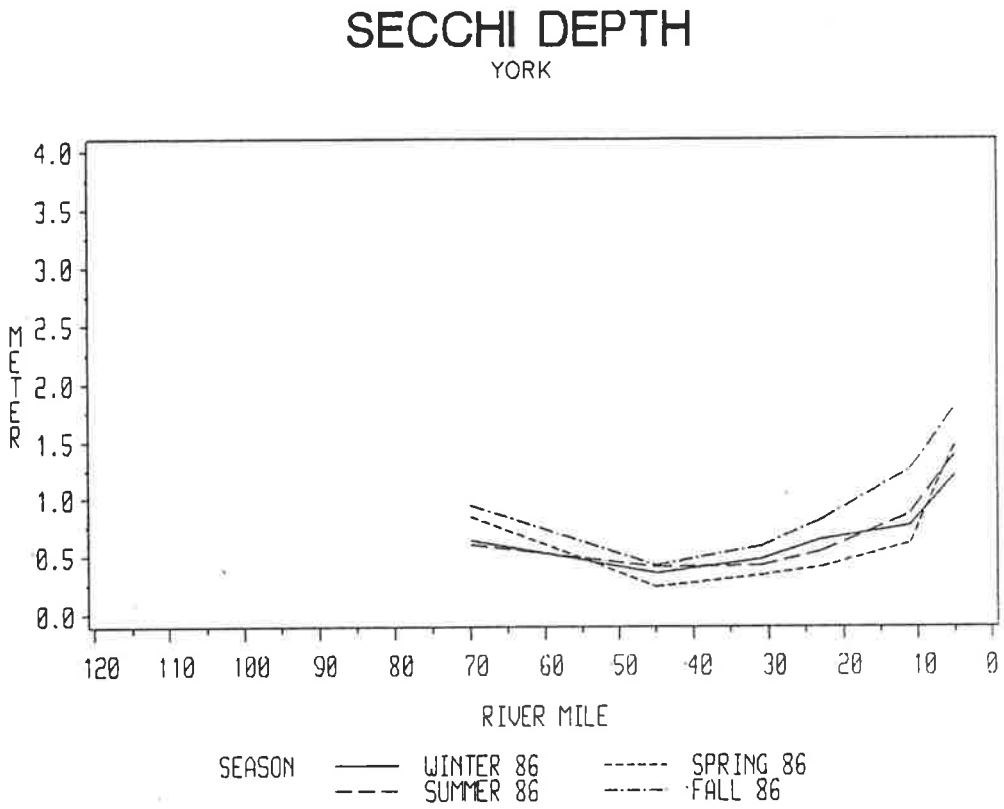


FIGURE 6.8



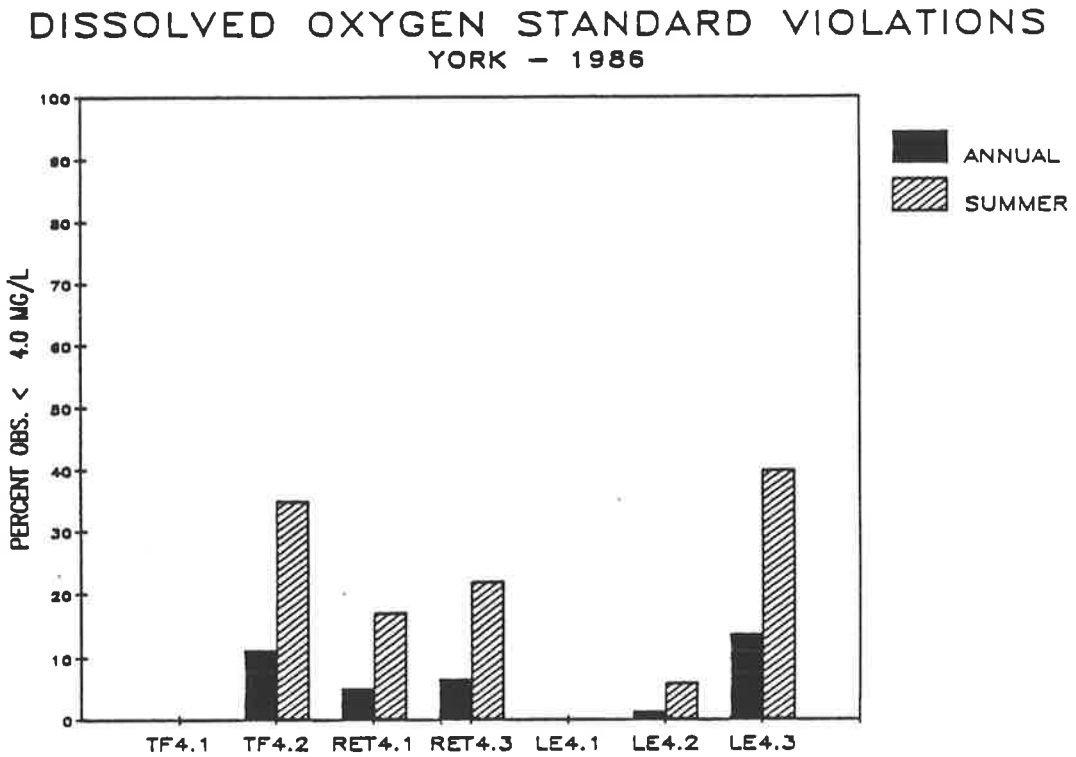
zone, but reached a minimum near mile 45, and remained low throughout much of the river until increasing sharply near the mouth of the river. Water clarity in the fall was higher than the other seasons, reflecting the very low streamflows.

DISSOLVED OXYGEN

In the York, violations of the dissolved oxygen standard are usually restricted to the channel near the mouth of the river, yet during 1986 the York also experienced hypoxia in the Pamunkey and upper tidal York (Figure 6.9). As is typical for the York river, the estuarine stations exhibited violations of the state's dissolved oxygen standard. On an annual basis, violations accounted for 2 - 14% of all observations. When examined on a seasonal basis, all violations occurred during the summer, with up to 40% of the observations below the standard during 1986 (Figure 6.9). The average summer dissolved oxygen concentration for stations in the lower York was between 4.5 and 5.5 mg/l. The station near the mouth of the York (LE4.3) typically experiences the lowest dissolved oxygen and during 1986 the minimum concentration observed there was 0.1 mg/l.

The occurrence of hypoxia in the lower York river has been linked to temporary stratification during neap tides, when mixing is greatly reduced between the surface and bottom layers. Shortly after spring tides, the strong tidal forcing results in a complete mixing of the system. The short term stratification results in lower oxygen concentrations and higher nutrient levels in the bottom waters. The CBP Benthic Monitoring Program has shown little evidence of long-term negative impacts to the

FIGURE 6.9



benthos, probably due to the temporary nature of the hypoxia, yet short term impacts on the benthos may be present and would be difficult to detect.

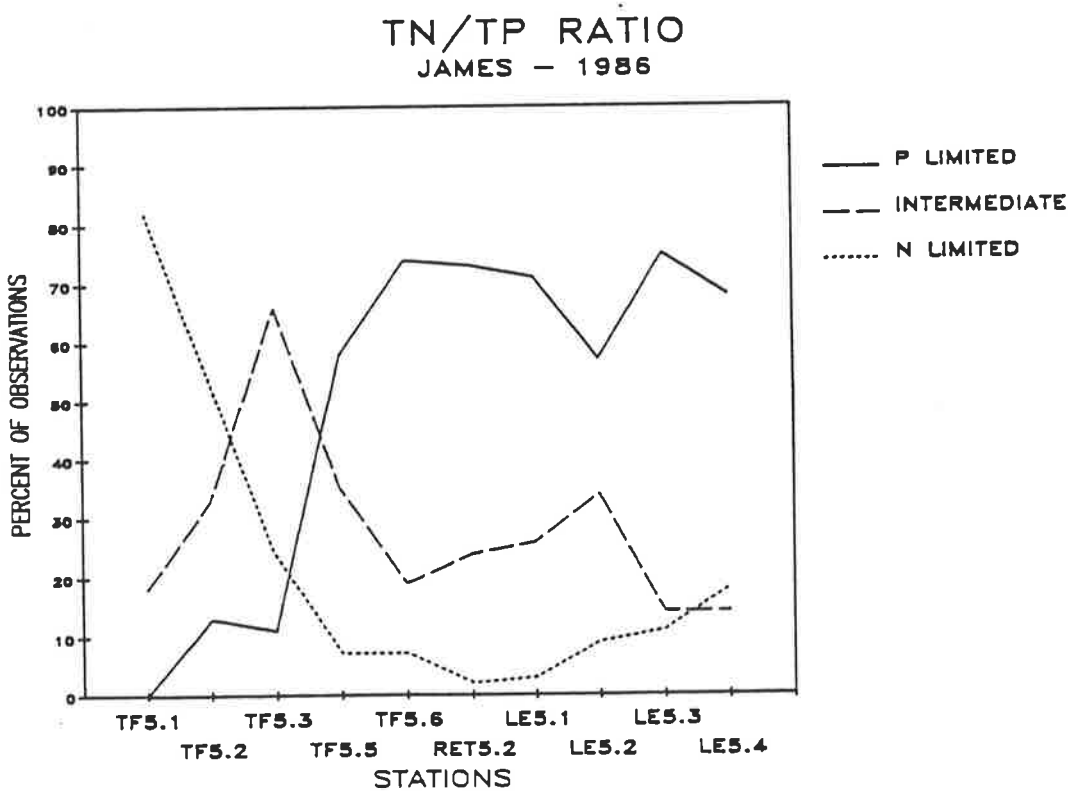
Unlike previous years, in 1986 the York exhibited a relatively large occurrence of low dissolved oxygen in the tidal freshwater and transition zone. The two tidal stations on the Pamunkey and station RET4.3, just down river from West Point on the York, all exhibited dissolved oxygen below the state standard. During the summer, 17 - 36% of the observations at these stations were below 4.0 mg/l, with minimum dissolved oxygen concentrations between 3.5 and 3.8 mg/l. The occurrence of low dissolved oxygen in this area of the York is not as severe as near the mouth of the river, but it did appear to be a persistent feature of this area of the river during 1986. Unlike the lower York, where hypoxia is restricted to the bottom waters, hypoxia was evident throughout the water column in the upper York. The hypoxia occurring in the upper York does not appear directly connected to the hypoxia near the mouth. Station LE4.1, located in between the two areas, did not experience violations of the standard during 1986. The differences in the characteristics of hypoxia in the upper river from those in the lower river suggests that it may be caused by a different mechanism, as yet undetermined.

JAMES RIVER

N/P RATIOS

In the James river, the higher instream concentrations of nutrients resulted in more TN/TP ratios being calculated, thus allowing for better interpretations and comparisons. There were 35 - 40 TN/TP ratios calculated for all stations except at the fall line and at the river's mouth, where only 10 - 20 ratios were calculated. In general, the TN/TP ratios indicate the upper James is nitrogen limited near the fall line, then becoming intermediate between nitrogen and phosphorus limited below the Richmond area dischargers, and becoming predominately phosphorus limited down river of the Hopewell area. At the fall line of the James, 82% of the TN/TP ratios indicated nitrogen limitation (Figure 6.10). The Mayo's Bridge station (TF5.2) also exhibited high occurrence of nitrogen limitation (55%), but with fewer occurrences of phosphorus limitation. Between Richmond and Hopewell (TF5.3) TN/TP ratios indicated that nutrient limitation was intermediate between nitrogen and phosphorus. Very little phosphorus limitation occurred at this station except during periods of high nitrate concentration in the spring. The large loading of nitrogen and phosphorus from Richmond area sewage treatment plants, which results in high instream concentrations, is also responsible for the shift from predominately nitrogen limitation at the fall line to intermediate ratios. Downstream of Hopewell, the TN/TP ratios increase sharply between TF5.3 and TF5.6 and remain relatively high down river, with 60 - 75% of the TN/TP ratios indicating phosphorus limitation. This increase in the TN/TP ratios is the result of an increase in nitrogen and a decrease in phosphorus concentrations.

FIGURE 6.10



The down river shift from nitrogen limitation to phosphorus limitation during 1986 was similar to, but more pronounced than, the pattern observed in 1985. The TN/TP ratios during 1986 indicated more nitrogen limitation at the fall line, and more phosphorus limitation in the estuary. At the fall line, phosphorus limitation was nearly absent during 1986, unlike 1985 when approximately 30% of the TN/TP ratios indicated phosphorus limitation. Downstream of TF5.6 during 1986, the occurrence of phosphorus limitation was greater and nitrogen limitation occurred less than during 1985. Phosphorus limitation occurred 40 - 60% of the time during 1985 compared to 60 - 80% during 1986.

CHLOROPHYLL-A

Of the three tributaries, the James has the highest loadings of nitrogen and phosphorus, and the highest instream concentrations. It is generally considered nutrient enriched and several previous monitoring programs have investigated nutrient and chlorophyll-a concentrations in the James. Analysis of the V.I.M.S. long-term slackwater surveys indicates a peak in chlorophyll-a during summer at mile 68, between Hopewell and the confluence of the Chickahominy River. During 1983-1985, the James River Water Quality Monitoring Program identified an increase in chlorophyll-a starting at river mile 99 and peaking between miles 65 and 75. Based on these previous reports, the stations TF5.5 (mile 75) and TF5.6 (mile 56) appear to be located on either side of the actual chlorophyll-a peak. Therefore, data from this program probably represents an underestimation of the actual maximum chlorophyll-a concentrations in the tidal freshwater James.

During 1986, the James experienced maximum chlorophyll-a concentrations in the tidal freshwater zone during spring, summer, and fall, with a more moderate peak in the estuary during winter (Figure 6.11). The typical winter/spring bloom of estuarine phytoplankton was indicated by the moderate chlorophyll-a concentrations at the estuarine stations. The maximum concentration was at mile 11 (LE5.4), where the chlorophyll-a concentration averaged 16 ug/l, with a maximum of 33 ug/l. The winter/spring bloom continued into April but was limited to near the mouth of the river.

The dominant feature of the chlorophyll-a concentrations in the James was the intense and persistent peak at mile 75 (TF5.5). The chlorophyll-a concentrations at mile 75 increased sharply between late March and early April and remained high through December (Figure 6.12). The seasonal average chlorophyll-a concentration for the spring, summer and fall was between 35 and 51 ug/l, with maximums of between 40 and 70 ug/l. The stations located up and down river of TF5.5 had fairly low chlorophyll-a concentrations except during July and August (Figure 6.12).

The section of river between Richmond and Hopewell had concentrations of inorganic nutrients as high as the section below Hopewell, but only experienced sporadic algal blooms. High turbidity has sometimes been identified as the limiting factor for algal growth in this area, but water clarity is generally higher than further downstream. A change in the hydrodynamics of the river, from a narrow, faster flowing, to a broader, slower flowing, river may be a major factor in the apparent differences. The additional nitrogen and phosphorus loading in the Hopewell area may also be responsible for some of the increase in chlorophyll-a.

FIGURE 6.11

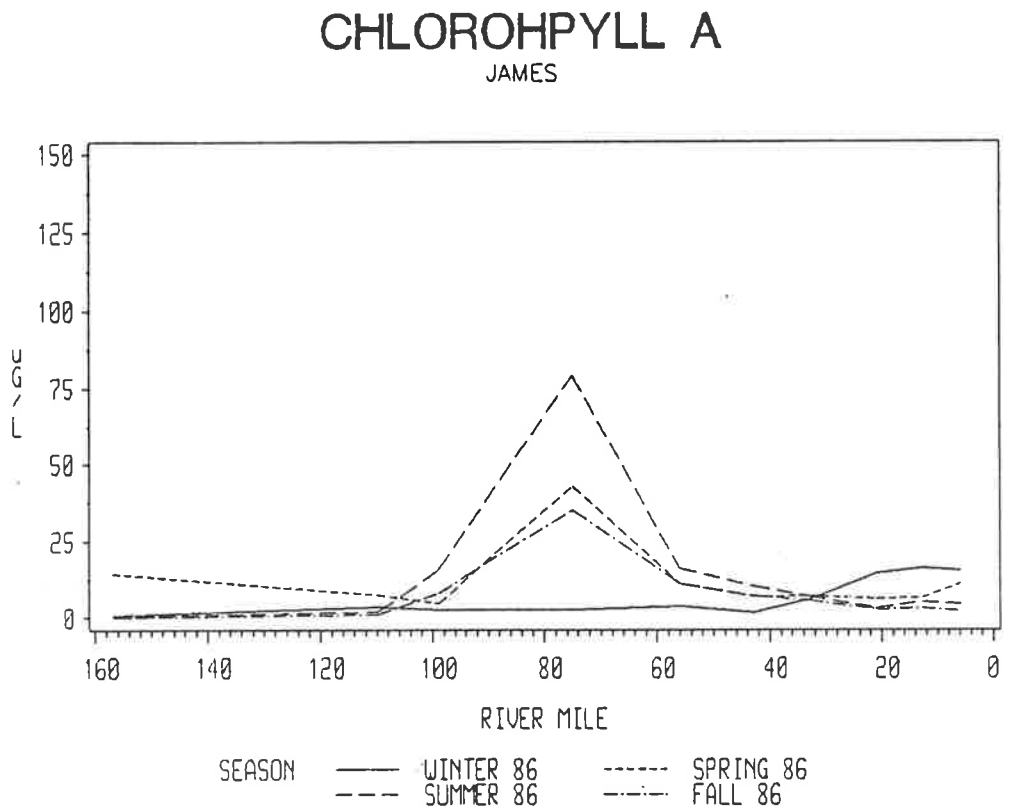
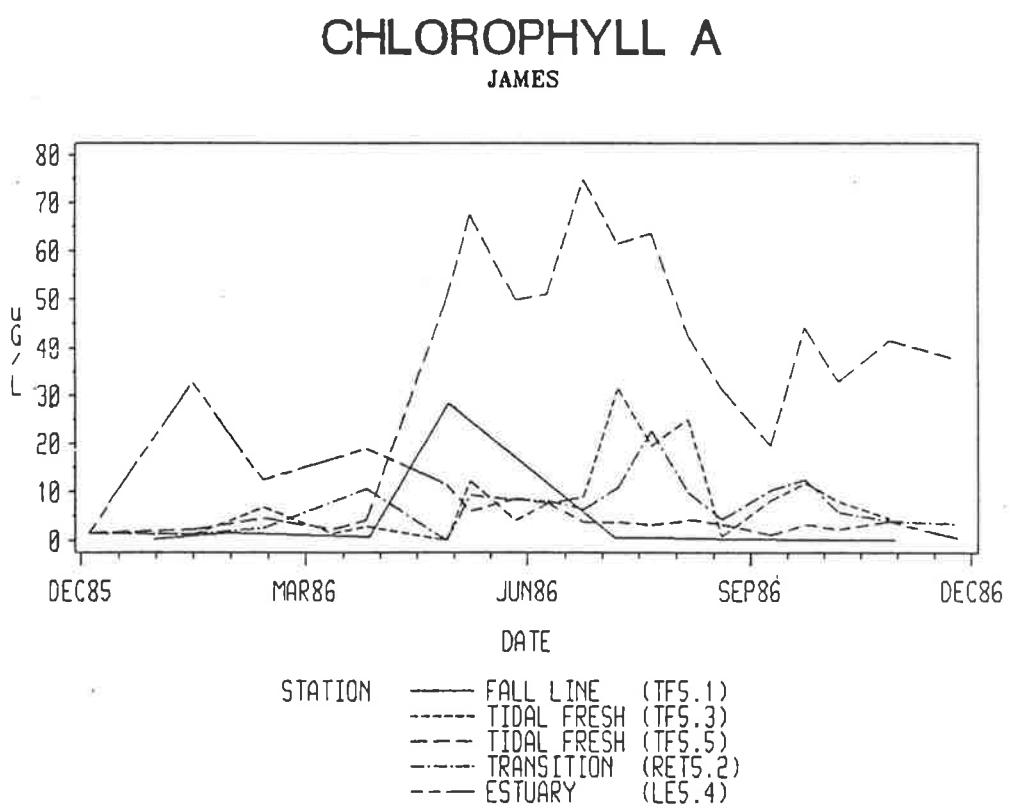


FIGURE 6.12



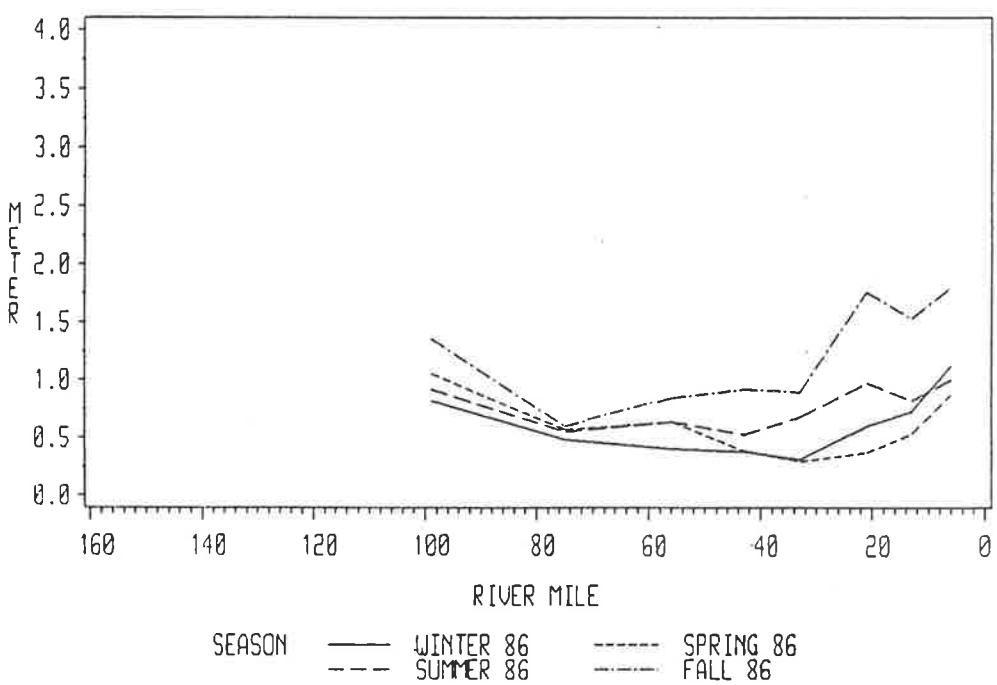
WATER CLARITY

Water clarity in the James was relatively high between Richmond and Hopewell (0.75 - 1.5 meters), decreased in the lower tidal freshwater and transition areas, then increased in the estuary (Figure 6.13). Water clarity in the James was highly variable, and the area of minimum water clarity varied seasonally over a broad area from Hopewell to below Jamestown Island. This area includes river miles 32 through 75, where salinity ranges from 0 to 5 ppt. In the winter, water clarity was the lowest in the upper tidal James, but increased toward the river mouth. During the spring, water clarity in the upper tidal James was greater, while the lower tidal James had lower water clarity. In the summer, water clarity in the upper tidal James was similar to the spring, but in the estuary water clarity was markedly higher. Water clarity was greatest throughout the river during fall, when the lower tidal James exhibited secchi readings of 2.0 meters, approximately 50% higher than in the other seasons.

FIGURE 6.13

SECCHI DEPTH

JAMES



DISSOLVED OXYGEN

The James river was relatively free of low dissolved oxygen events during 1986. Violations of the State standard occurred only during the summer at station LE5.6 (10%). This station is located at the mouth of the Elizabeth river, which is a highly industrialized and developed basin. No violations were recorded in the upper tidal James near Richmond or Hopewell. The more spatially intensive monitoring conducted by the Richmond Regional Planning District Commission during 1984-1985 identified a dissolved oxygen sag below Richmond, and another below the Hopewell area. Neither sag resulted in dissolved oxygen concentrations below State standards during those years. Data from the VIMS slackwater surveys, from 1970 to 1985, show a reduction in the occurrence of low dissolved oxygen in the upper tidal James over the last decade.

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RIVER COMPARISONS

N/P RATIOS

When examining the results of the response variables from the James, York, and Rappahannock, some important contrasting characteristics become evident. The TN/TP ratios for the three river systems provide a good example of these contrasts. During 1986, the Rappahannock and York exhibited equal frequencies of nitrogen and phosphorus limitation at the fall line, but the James was predominately nitrogen limited. The tidal freshwater of the Rappahannock and York were phosphorus limited while the James exhibited a wide range of nitrogen and phosphorus limitation. The low streamflow during 1986 may have resulted a higher occurrence of nitrogen limitation at the fall line, due to lower nitrogen concentrations. The predominance of nitrogen limitation near the fall line of the James contradicts the traditional view that freshwaters are normally phosphorus limited. The much higher phosphorus concentrations at the fall line of the James represents a major deviation from typical conditions for free flowing streams, resulting in nitrogen limitation. In the tidal freshwater areas of the James, the nitrogen and phosphorus loadings from non-point and point sources and subsequent processing within the river results in a complex range of nutrient concentrations and ratios. Any nutrient management strategy for the tidal James must take in to account the large phosphorus contribution from above the fall line as well as the phosphorus and nitrogen loadings from point sources in the tidal waters.

The transition stations in the York appear to have a lower occurrence of phosphorus limitation than either the James or the Rappahannock rivers. This is largely a function of the increase in phosphorus seen in this section of the York. The estuarine section of the three rivers appear similar, with 60 - 80% of the TN/TP ratios indicating phosphorus limitation. The estuarine area has the lowest nitrogen and phosphorus concentrations and thus the fewest number of ratios calculated, so seasonal comparisons are limited, especially in the summer. Recent microcosm research has indicated that the estuarine waters of the Chesapeake Bay may be phosphorus limited in the winter and nitrogen limited in the summer. These seasonal changes are in part due to high nitrogen loadings from increased streamflow in the winter/spring resulting in phosphorus limitation, while in the summer during low streamflows with less nitrogen loading, nitrogen becomes limiting. Loss of nitrate through denitrification, and increased release of phosphorus from the sediment may also contribute to nitrogen limiting conditions during the summer.

CHLOROPHYLL-A

Chlorophyll-a concentrations during 1986 indicate that prolonged and intensive blooms of freshwater phytoplankton occur in the Rappahannock and James. Both the Rappahannock and James exhibit chlorophyll-a concentrations in tidal freshwater greater than 25 ug/l, with maximums exceeding 40 ug/l. During the winter of 1986, moderate blooms of estuarine phytoplankton were apparent in the estuarine areas of all three rivers (Figure 6.14A). The estuarine blooms continued into the spring in the Rappahannock and York rivers, but were not as evident in the James. By spring, the James was already exhibiting an intensive freshwater algal bloom near mile 80 (Figure 6.14B). During the summer both the tidal

freshwater Rappahannock and James exhibited chlorophyll-a peaks of 51 and 26 ug/l, respectively. During the summer, the estuarine segments of the rivers generally exhibited chlorophyll-a concentrations below 15 ug/l with a few short-term blooms (Figure 6.14C). The fall, with its low streamflows and higher salinities, was very similar to the summer. Chlorophyll-a peaks in the tidal freshwater sections of the Rappahannock and James were as intensive and persistent as during the summer (Figure 6.14D). The data from the Rappahannock seems to indicate a fall bloom of estuarine phytoplankton, which is typical for estuarine waters, but is usually of shorter duration and intensity than the winter/spring bloom.

The James, with the highest phosphorus concentrations of the three rivers, experiences the most intense and prolonged tidal freshwater blooms. The Rappahannock, with low phosphorus but high nitrate concentrations, experienced tidal freshwater blooms of less intensity and shorter duration than the James. The Rappahannock also had the greater blooms of estuarine phytoplankton, both in the winter/spring and the fall. In contrast, chlorophyll-a peaks in the York river were much less intense and always located in saline waters.

WATER CLARITY

Water clarity was usually at a minimum in the transition or 'turbidity maximum' zone of the three rivers (mile 30-50), but a large portion of the tidal freshwater James also exhibited low water clarity. This may be due both to high suspended sediment and high algal concentrations. During the winter, water clarity in the Rappahannock was often twice as great as in the York or James (Figure 6.15A). This may be due to the importation into the Rappahannock of relatively clear water from the central Chesapeake Bay. The water clarity in the York and James may be influenced by the low water clarity of the Bay water near their mouths. During the spring and summer, water clarity remained fairly low throughout the rivers due to relatively high streamflows in the spring and algal biomass during the summer (Figure 6.15B). The extremely low streamflows and higher salinities that occurred in the fall of 1986 resulted in a substantial increase in water clarity, particularly in the estuarine portion of all three rivers.

FIGURE 6.14A

CHLOROPHYLL A

ALL RIVERS – WINTER 1986

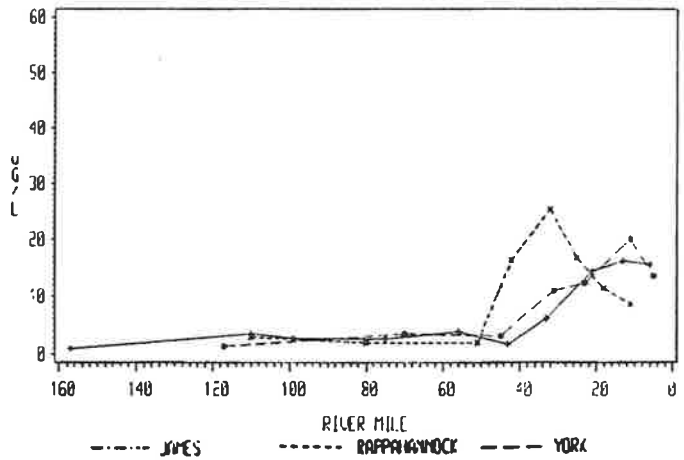


FIGURE 6.14B

CHLOROPHYLL A

ALL RIVERS – SPRING 1986

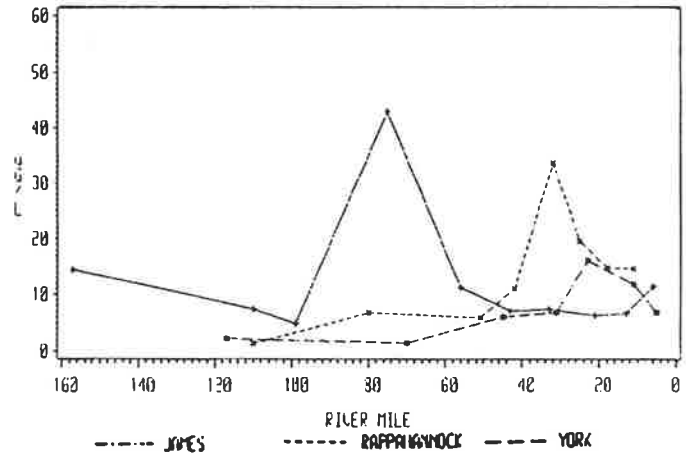


FIGURE 6.14C

CHLOROPHYLL A

ALL RIVERS – SUMMER 1986

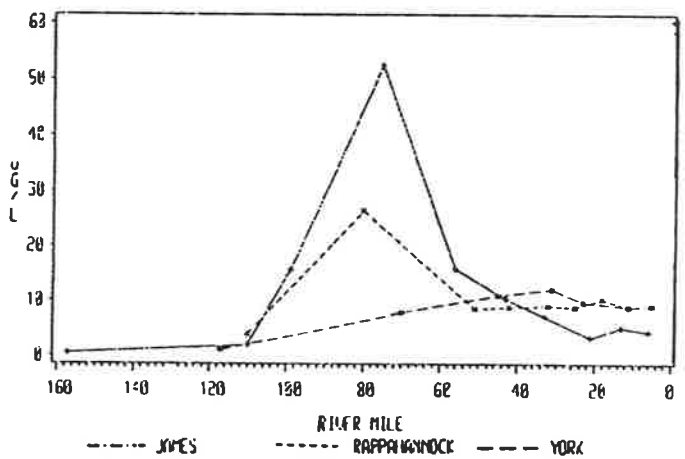


FIGURE 6.14D

CHLOROPHYLL A

ALL RIVERS – FALL 1986

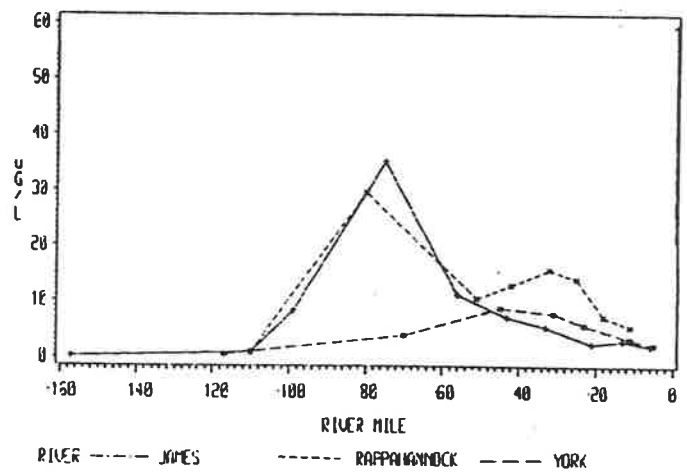


FIGURE 6.15A

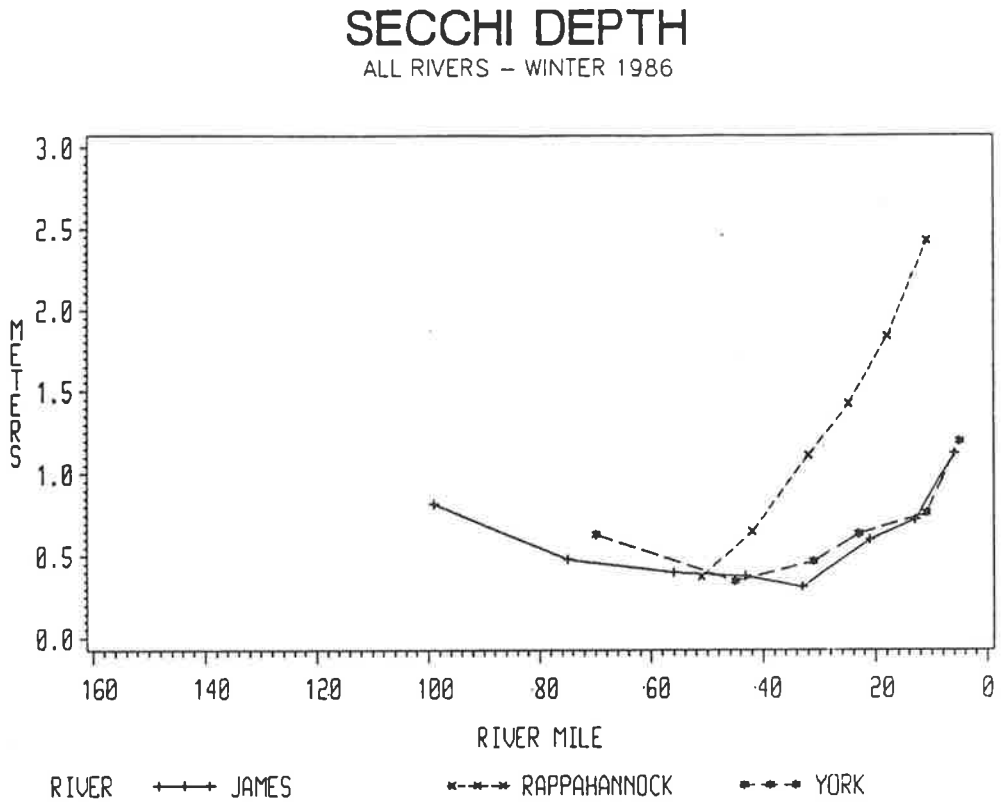
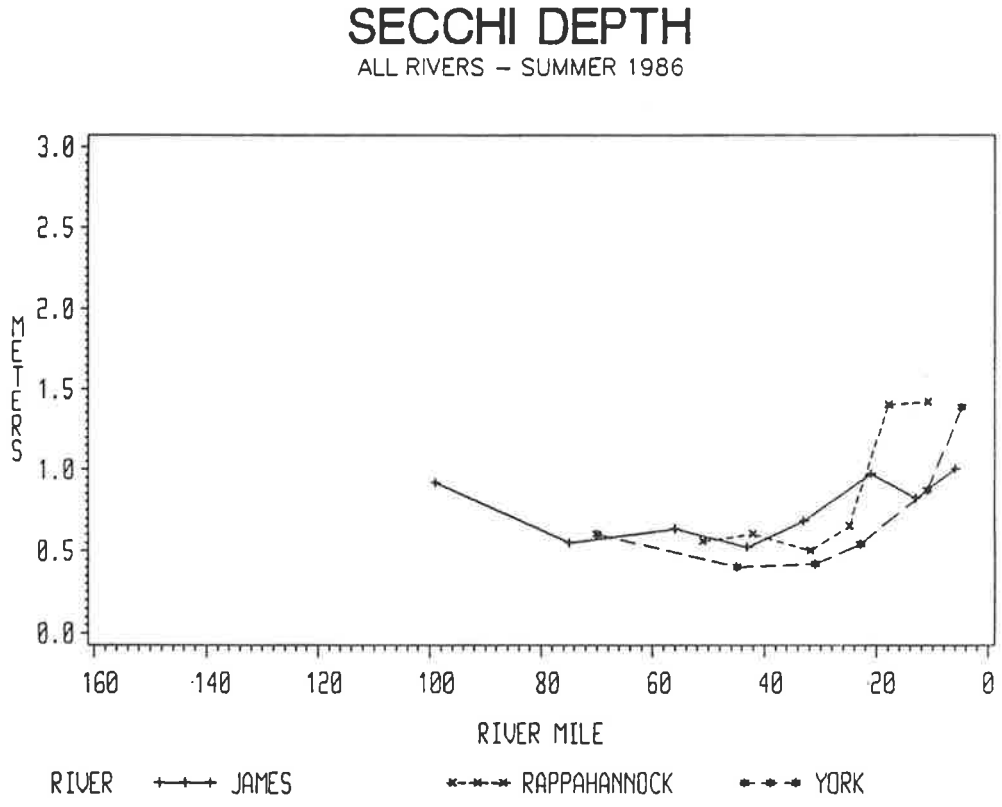


FIGURE 6.15B



DISSOLVED OXYGEN

Contrary to intuition, the river subjected to the most urban and industrial development, the James, experiences the least occurrence of low dissolved oxygen or hypoxia. Isolated occurrences of low dissolved oxygen were reported in the James, but they were usually associated with urban areas. Near the mouth of the Rappahannock and York, 20 - 40% of the dissolved oxygen concentrations during the summer of 1986 were below 4.0 mg/l, with minimums well below 1.0 mg/l. The occurrence of hypoxia near the mouth of the Rappahannock was more prolonged and covered a larger area than in the lower York. The York also exhibited dissolved oxygen concentrations between 3.0 and 4.0 mg/l during the summer in the tidal freshwater and transition areas. This area of low dissolved oxygen appears to occur separately from the hypoxia in the lower York and is probably caused by a different mechanism, not yet explained.

The lack of hypoxia in the James may be attributed to the strong and complex circulation in the lower James which allows for more vertical and lateral mixing. This, combined with shorter residence times may be keeping the water column well aerated. Kuo and Neilson (1987) have suggested that the difference in longitudinal salinity gradients between the three rivers is responsible for the occurrence of hypoxia in the Rappahannock and lack of it in the James. The upriver flow of saline water along the bottom of the James is much stronger than in the Rappahannock, thus resulting in a shorter residence time for water in the James than in the Rappahannock. The shorter residence time in the James does not allow enough time for water column and sediment oxygen demands to reduce oxygen concentrations to hypoxic levels. In the Rappahannock, the longer residence time allows the slower upriver flow of the bottom layer enough time for oxygen demands to produce hypoxia. Another factor under investigation in the Rappahannock is the possibility that central Chesapeake Bay water flowing into the Rappahannock is already low in oxygen. Hypoxic waters from the main channel of the Bay may be spilling over the sill at the mouth of the Rappahannock during certain tidal conditions or storm events. The Bay waters at the mouth of the James and York generally do not experience hypoxia as does the waters off the mouth of the Rappahannock.